Estimates of Electricity Requirements for the Recovery of Mineral Commodities, with Examples Applied to Sub-Saharan Africa

Open-File Report 2011–1253

U.S. Department of the Interior
U.S. Geological Survey

Cover. High voltage power lines over the San Andreas Fault at Cajon Pass, California. Photograph by Don Becker, U.S. Geological Survey.

Estimates of Electricity Requirements for the Recovery of Mineral Commodities, with Examples Applied to Sub-Saharan Africa

By Donald I. Bleiwas

Open-File Report 2011–1253

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

Suggested citation:
Bleiwas, D.I., 2011, Estimates of electricity requirements for the recovery of mineral commodities, with examples applied to sub-Saharan Africa: U.S. Geological Survey Open-File Report 2011–1253, 100 p.

Contents

Figures

Appendix Figures

Tables

Appendix Tables

Conversion Factors

Except for the use of kilowatts, most measurements in this report are in metric units. Conversion factors are provided below. In this paper the metric ton is referred to as "ton."

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
	Volume	
gallon (gal)	3.785	liter (L)
cubic foot (ft3)	0.02832	cubic meter (m3)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 pounds)	0.9072	metric ton (t)
ounce, troy (ozt)	32,150.7	metric ton (t)

SI to Inch/Pound

Multiply	By	To obtain
	Energy	
joule (J)	0.0000002	kilowatthour (kWh)
gigajoule (GJ)	277.8	kilowatthour (kWh)

SI Conversions

Multiply	By	To obtain
	Mass	
part per million (ppm)	1,000,000	metric ton (t)
	Energy	
kilowatt (kW)	1,000	watt (W)
megawatt (MW)	1,000	kilowatt (kW)
gigawatt (GW)	1,000	megawatt (MW)
terawatt (TW)	1,000	gigawatt (GW)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

Estimates of Electricity Requirements for the Recovery of Mineral Commodities, with Examples Applied to Sub-Saharan Africa

By Donald I. Bleiwas

Introduction

To produce materials from mine to market it is necessary to overcome obstacles that include the force of gravity, the strength of molecular bonds, and technological inefficiencies. These challenges are met by the application of energy to accomplish the work that includes the direct use of electricity, fossil fuel, and manual labor. The tables and analyses presented in this study contain estimates of electricity consumption for the mining and processing of ores, concentrates, intermediate products, and industrial and refined metallic commodities on a kilowatt-hour (kWh) per unit basis, primarily the metric ton (ton) or troy ounce. Data contained in tables pertaining to specific currently operating facilities are static, as the amount of electricity consumed to process or produce a unit of material changes over time for a great number of reasons. Estimates were developed from diverse sources that included feasibility studies, company-produced annual and sustainability reports, conference proceedings, discussions with government and industry experts, journal articles, reference texts, and studies by nongovernmental organizations (NGOs). Suggestions for additions and corrections are welcome by the author.

Analytical Applications of Electricity Consumption Estimates

Estimates of electricity consumption can be applied to a wide range of analyses. For example, the tables can be used to (1) perform or review prefeasibility level studies by using individual estimates or linking them for estimating requirements for vertical integrated mining operations; (2) estimate the economic effects of changes in power rates and fuel costs on producing or planned mining facilities; (3) estimate a component of greenhouse gas contributions produced by the energy source used to generate electricity consumed by a mining operation. For example, burning coal produces over 50 percent more carbon/kWh than natural gas (CCL, 2011); (4) estimate the power requirements for a sector of the minerals industry by commodity or geographic area; (5) estimate power requirements for future mineral resource development on existing or planned grids; (6) examine the effects of investment in development of underutilized sources of electricity generation, such as hydropower, that may support mineral development; and (7) evaluate potential effects on mineral commodity production as a result of inadequate and interrupted electricity supply.

Limitations on Use of Estimates

For the aforementioned reasons and those listed below, the estimates presented in the following tables are considered "back of the envelope" and in many cases should be considered as prefeasibility level estimates, ±25 percent of actual per unit electricity consumption, especially for cumulative estimates (mining through marketable product), and perhaps even greater when applied to a particular site where mining and beneficiation is included. They are "rule of thumb" estimates and have value for undertaking prefeasibility level estimates of electricity requirements. The development of an accurate estimate for any particular site requires more information than is generally available in publicly available literature.

The following assumptions or methods used to develop estimates should be among the considerations when performing analyses using the data presented in the tables:

1. Estimates are based on consumption of electricity on a per unit time basis (kWh) and by unit of weight for ore, concentrate, matte, and refined mineral commodity production—not demand expressed as kilowatts (kW). An explanation of the difference between kWh and kW can be found in Think Energy Management LLC (2010).
2. The inefficiencies and losses in generation, transmission, and distribution of electricity prior to entering a facility are not relevant to the analyses performed, but should be considered when examining the burden placed on the electrical grid or a particular generating facility. Electricity transmission loss in some countries exceeds 30 percent from the point of generation to the point of delivery (Cleantech Group LLC, 2011). In the United States, transmission losses are approximately 10 percent (National Council on Electric Policy, 2004). In comparison, in Ghana, which has a relatively large gold mining presence, transmission losses are estimated at nearly 18 percent (Trading Economics, 2011).
3. Electricity consumed at a site can be procured in part or in whole from a power grid, or generated in part or in total by on-site or offsite facilities independent of the grid. For example, sand and gravel operations, alluvial mining operations, and facilities in remote areas often generate electricity independent of a grid using on-site, diesel-fueled generators.
4. Inefficiencies that affect electricity consumption in a facility can occur for many reasons. For example, operation of equipment at levels less than optimum efficiency can occur in response to labor and technical problems and/or economic conditions. Electricity consumed during care and maintenance or during periods of reduced production was not considered. For example, ventilation and pumping of water (dewatering), which are relatively significant consumers of electricity, can continue in underground mines with reduced ore production or during care and maintenance.
5. Most estimates were based on actual or proposed facilities operating at or near design capacity.
6. Unless otherwise noted, the electricity requirements for certain ancillary services are not included in the electricity consumption estimates. These could include on-site administrative facilities (office equipment, cooling and heating, and lighting), workers' living quarters, potable water and sanitation facilities, unloading and loading activities, and town sites. Other uses of electricity not directly related to the on-site processing of ores, concentrates, and other materials employed to produce commodities, such as

corporate offices located offsite, are not included in the estimates. These can be significant consumers of electricity, but are relatively low when prorated against ore production.

7. Electricity used in the production of equipment, parts, construction materials (such as cement and steel), consumables (such as balls, rods, and linings), anode paste, fuels, reductants, and other reagents manufactured offsite and transferred to or purchased by a facility are not included in the estimates. In some cases, electricity requirements for facilities such as sulfuric acid plants and oxygen plants are included.
8. Electricity consumption for mining a surface or underground deposit can vary significantly from one site to another owing to numerous factors that include: waste-to-ore ratio and dilution, mining method and mine equipment selection, mine depth, extent of workings, distance to working faces (which, in addition to types of equipment employed, determines ventilation requirements and if refrigeration of air is necessary), and requirements for dewatering (pumping). Examples include a group of gold and platinum-group-metal operations in South Africa that extract ore from deep underground mines that employ refrigerated ventilation, multi-stage pumping, specialized compressors, and other types of equipment to meet requirements that are not commonplace in the minerals industry. Mine ventilation, a significant use of electricity for underground mines, requires roughly 10 short tons (st) of fresh air to be circulated for each st of ore extracted; however, the hottest and deepest mines, like some of the precious metal mines in South Africa, can use up to 20 st of fresh air for each st of ore mined. The deep South African mines can require 254 cubic feet per minute (cfm) of refrigerated air per t of ore mined per day, as compared to about 100 cfm per t of ore mined for most underground mines (Stantec Inc., 2010).

Major factors that affect the amount of electricity required for the recovery of commodities post-mining include: (1) ore grade and mineralogy; (2) size of material delivered to the crusher; (3) crushing and grinding characteristics such as Bond work index; (4) separation technologies such as flotation, gravity, leach, and pyrometallurgical versus electrolytic refining; and (5) treatment and placement of waste. For example, the ore hardness, brittleness, and size reduction of ore to optimize recoveries are major determinants in the amount of electricity required during the grinding stage. Over 90 percent of the required external energy required to perform the work is in the form of electricity. The amount of energy necessary to beneficiate ore, especially in the grinding stage, is also very sensitive to ore grade when expressed as kWh per unit of recovered copper cathode and can be misleading. As a simplified example, if 20 kWh are required to crush and grind a ton of ore grading 0.5 percent copper, the amount of electricity required to recover one ton of copper is about 4,500 kWh, based on an overall copper recovery of 88 percent. However, if the ore grade is 1 percent copper and all other factors remain the same, roughly one-half the amount of energy is required per t of copper recovered, disregarding economies of scale. The presence of co- or byproduct minerals associated with ore must be considered when expressing kWh/t against a single commodity.

Other estimates are derived from sources that describe electricity consumption in terms such as "typical" or "average" for mining, beneficiation, smelting, and refining technologies. Using these types of estimates is less of an issue for post-beneficiation technologies, such as smelting and refining. The consumption of electricity per unit of commodity recovered is generally similar from site to site when employing state-of-the-art patented technologies.

9. Electricity consumption for smelting and refining is affected to varying extents by multiple factors, such as the composition of feedstock. For example, concentrates high in sulfide minerals are exothermic when oxygen is supplied, which therefore reduces the amount of direct energy needed to melt the material. The success of flash furnace technology relies on the heat of oxidation reaction. The refractory nature of the molecular bond is also a major component that determines the energy required to liberate an element. Concentrates that contain MgO require more heat to form a melt. The amount of electricity required to go from alumina to aluminum is highly energy intensive because of the bond strength of oxygen. In general, the electricity consumption for all aspects of mining through the production of a final product is affected by the age, type, and design of equipment.
10. Operations may switch from electrically powered equipment to diesel powered equipment on a temporary or permanent basis because of concerns regarding the availability, cost, or other limitations of electricity. The reverse can also occur.
11. Electricity consumed for surface transportation of materials produced at the facilities, with the exception of conveyor belts, is usually fossil-fuel dependent (trains pulled by diesel-electric locomotives and trucks) and is not included in the estimates.
12. Power index conversions from volt-amps to watts vary from site to site. In some cases, electricity requirements for an operation were estimated from the amount of diesel fuel consumed by generators for producing electricity on site. The estimates using this method are based on limited site information. Diesel fuel contains about 9.7 kWh/liter (kWh/l) of energy, but when used in well-maintained generators, roughly 4 kWh/l is produced (Williams, 2010; Natural Resources Canada, 2009). The balance of the energy is lost through inefficiencies introduced through generation of heat from combustion, friction, incomplete combustion, and other factors. See table 1 for estimates of kWh of electricity contained and generated from major types of fossil fuels used in generators.

References

Brown, M. H., and Sedano, R. P., 2004, Electricity transmission—A primer: National Council on Electric Policy, last accessed June 2, 2011, at *http://www.raponline.org/docs/NCSL_Brown_ElectricityTransmissionPrimer_2004_06.pdf*.

Cleantech Group LLC, 2011, India loses 45% of the electricity it produces—expect surge in energy efficiency investment in Cleantech Insights: last accessed June 2, 2011, at *http://blog.cleantech.com/sector-insights/energy-efficiency/india-loses-45-of-the-electricity-it-produces-expect-surge-in-energy-efficiency-investment/*.

Climate Change Levy (CCL), 2011, Information sheet 12—Sources of energy: last accessed May 17, 2011, at *http://www.cclevy.com/more_info.asp?current_id=174*.

Natural Resources Canada, 2009, Power-Wind turbine-390kW-Isolated-grid/Canada: last accessed January, 25, 2011 at *http://www.retscreen.net/ang/case_studies_390kw_isolated_grid_canada.php*.

Stantec Inc., 2010, Hard rock miner's handbook rules of thumb, Chapter 18—Ventilation and air conditioning: last accessed January 24, 2011, at *http://www.mcintoshengineering.com/*

HardRockMinersHandbook/HardRockMinersRulesofThumb/VentilationandAirConditioning/tabid/95/Default.aspx.

Think Energy Management LLC, 2010, Understanding demand and consumption: last accessed September 11, 2010, at *http://www.think-energy.net/KWvsKWH.htm*.

Trading Economics, 2011, Electric power transmission and distribution losses: last accessed June 2, 2011 at *http://www.tradingeconomics.com/ghana/electric-power-transmission-and-distribution-losses-kwh-wb-data.html*.

Williams, David, 2010, Bella Coola smart grid: Okanagan College, last accessed January 25, 2011, at *http://www.elen.ca/energy/bella-coola-smart-grid/*.

Table 1. Estimated efficiencies for the conversion of selected fossil fuels to electricity.

[Estimates are rounded to two significant figures. kWh, kilowatt hour; t, metric ton; l, liter; m^3, cubic meter]

Fuel type	Estimates of contained kWh/unit of fuel	Unit	Range of efficiency estimates of fossil fuel conversion to electricity, percent[1]	Estimated kWh/unit of fuel[2]
Coal (lignite-anthracite)[3]	4,100–10,000	t	35–40	1,500–3,800
Diesel oil	9.7	l	35–44	3.8
Heavy fuel oil	12	l	35–44	4.5
Natural gas	11	m^3	33–49[4]	4.5

[1] Estimates are for converting energy contained in fuel to electricity prior to transmission and do not include load factors. Plant efficiency can be affected by numerous factors, including ambient conditions, design, fuel type and quality, operational practices, and pollution controls. Estimates assume full load.

[2] Based on the simple average of the range of values of power plant fuel conversion efficiencies.

[3] Energy values in coal can vary significantly and assume complete combustion, which is not always the case.

[4] Within the range estimate, conventional gas turbines represent the lower values and combined-cycle-gas-turbines represent the higher values.

References for Table 1

Bellman, D. K. and others, 2007, Topic paper #4—Electric generation efficiency: The National Petroleum Council, Global oil & gas study, last accessed on April 12, 2011, at *http://www.npc.org/Study_Topic_Papers/4-DTG-ElectricEfficiency.pdf.*

Coal Geology, 2010, Coal classification and analysis—Coal rank, classification by heat value: last accessed April 11, 2011, at *http://coalgeology.com/coal-classification-and-analysis-coal-rank-classification-by-heat-value/8603/.*

E8, 2006–2011, Energy efficiency measures and technological improvements: E8, last accessed April 12, 2011, at *http://www.e8.org/index.jsp?numPage=138.*

Eurelectric (Union of the Electricity Industry), 2003, Efficiency in electricity generation: last accessed on April 11, 2010, at *http://docs.google.com/viewer?a=v&q=cache:n6OEqkMGSpsJ:www.eurelectric.org/Download/Download.aspx%3FDocumentID%3D13549+Eurelectric+%28Union+of+the+Electricity+InduIndu%29,+2003,+Efficiency+in+electricity+generation&hl=en&gl=us&pid=bl&srcid=ADGEEADGEESgNghREHiG7H0Mrp0OnZyxWgpj6vGEsCE83-Zqm6FQf9-ns4qDrKuOuw9Bhn4RTTYOp_BnD3gbRiiRf_wwxJRSS9gm7uyjw0-lRNgQmz9NQeUXx6sCxcFX0RwPi0T89n9F&sig=AHIEtbQUPwAc-CGiGNBJDI031Jjld4PP0Q.*

Norgate, T.E. and Rankin, W.J., 2000, Life cycle assessment of copper and nickel production: last accessed April 1, 2011 at *http://www.minerals.csiro.au/sd/CSIRO_Paper_LCA_CuNi.htm.*

Raja, A.K. , Srivastava, P.A., and Dwivedi, Manish, 2006, Power plant engineering: New Delhi, India, New Age International Publishers, 492 p.

RenewableUK, 2010, Efficiencies and load factors in electricity production: Fact sheet 05, last accessed April 11, 2011, at *http://www.bwea.com/pdf/briefings/FS05_Efficiencies_Load_Factors.pdf.*

Spath, P.L. and Mann, M.K., 2000, Life cycle assessment of a natural gas combined-cycle power generation system: NREL/TP-570-27715, 32 p., and an un-numbered appendix last accessed April 11, 2011, at *http://www.nrel.gov/docs/fy00osti/27715.pdf.*

Williams, David, 2010, Bella Coola smart grid: Okanagan College, last accessed January 25, 2011 at *http://www.elen.ca/energy/bella-coola-smart-grid/.*

Examples of an Application of Electricity Consumption Data

The following section presents brief analyses illustrating the application of electricity consumption data to the mining sector in sub-Saharan Africa.

Electricity Production in Sub-Saharan Africa

The electricity requirements of the mining industry in sub-Saharan Africa are met mostly by government-owned suppliers through independent and interconnected grids. By country, these include: (1) Botswana Power Corporation (BPC); (2) Democratic Republic of Congo's (Kinshasa) Socíeté Nationale d' Électricité (SNEL); (3) Ghana's Electric Corporation of Ghana (ECG) and Volta River Authority (VRA) (University of Ghana, 2005); (4) Electricidade de Mocambique (EDM) of Mozambique; (5) Namibia's Namibia Power Corporation (Pty) Ltd. (NamPower); (6) Nigeria's National Electric Power Authority, Brown Boveri (Nigeria) Limited, Ibom Power Company, and the Trans-Africa Gas and Electric Company, Plc.; (7) Eskom Holdings Ltd. in South Africa; (8) Tanzania Electric Supply Company, known as TANESCO, in Tanzania; (9) Zambia's Copperbelt Energy Corporation PLC (CEC), which generates some power for its mining customers, and Zambian Electrical Supply Corporation (ZESCO); and (10) ZESA Holdings (Pvt) Ltd., and its subsidiary Zimbabwe Power Company (ZPC) in Zimbabwe (AfDevInfo, 2010; Briceño-Garmendia, Smits, and Foster, 2008; Trinity International, 2010).

Some mining operations, smelters, and refineries also have "captured" electricity generating plants using fossil fuels and/or hydroelectricity owing to their remote locations and/or to ensure a reliable power supply. In some cases, the generating facilities have been attached to existing power grids as part of cooperative agreements.

Eskom is by far the largest of all electricity suppliers in sub-Saharan Africa. The company generates 95 percent of the electricity used in South Africa and 45 percent of the electricity used in Africa. The company produced an average of approximately 206,000 gigawatt hours (GWh) per year for the reporting years 2008 through 2010. A relatively small amount of electricity was also generated by other South African energy producers. The South African mining industry was reported by Eskom to have consumed an annual average of nearly 32,000 GWh, or about 15 percent of their delivered power during the period 2008 through 2010. In fiscal year 2010 (April, 2009 through March, 2010), Eskom exported approximately 13,200 GWh to other countries (see fig. 1) (Eskom Holdings Ltd., 2010). Figure 2 illustrates the percentage distribution of 26 terrawatt hours (TWh) consumed by selected mineral commodity industries in South Africa in 2005 (adapted from Hughes and others, 2006). In 2010, the increased share of electricity consumed for gold and PGM production was probably the result of elevated precious-metal prices (roughly double their previous price) which spurred higher production.

Southern African countries and their percentage share of Eskom's energy exports included Botswana (20 percent), Lesotho (less than 1 percent), Mozambique (63 percent), Namibia (11 percent), Swaziland (5 percent), Zambia (less than 1 percent), and Zimbabwe (less than 1 percent) (Eskom Holdings Ltd., 2010). Statistics on the amount of exported electricity consumed by the minerals industry in these countries were not available. Table 1 lists the electricity generation capacity and their share of the total capacity for selected countries in sub-Saharan Africa in 2008. South Africa represents nearly 70 percent of the generating capacity among the listed sub-Saharan countries. The United States is included in the list for the purpose of comparison.

In recent years, the mining sector in some sub-Saharan countries has experienced constraints on the availability of electricity because of increased consumption in sub-Saharan Africa's residential sectors, declining conditions of existing infrastructure, lack of reinvestment, several years of drought, and other events. In Zimbabwe, the electricity supply is prone to frequent outages and is perhaps the greatest infrastructure problem confronting the country's mining sector (Kaseke, 2010).

The United States International Trade Commission reported that financial commitments to electric power projects in sub-Saharan Africa increased in 2007 over the previous year by 62 percent to $3.9 billion, including funding from the World Bank and other traditional multinational and bilateral project financiers. Nevertheless, the World Bank estimated that the electricity sector in sub-Saharan Africa requires financing of about U.S. $8.3 billion annually between 2005 and 2015 to upgrade plants and equipment (U.S. $5.2 billion) and to provide for adequate operation and maintenance (U.S. $3.1 billion). The World Bank is the principal lender and guarantor in the sub-Saharan Africa electric power sector (U.S. International Trade Commission, 2009). Actual expenditures, as opposed to commitments, have not been analyzed in detail.

Mining companies in South Africa and other countries have responded to the shortage of electricity and recently emplaced and proposed higher electricity costs by placing greater emphasis on increasing the efficiency of power use, reducing production, and constructing or planning captured generating plants (Hassan, 2007; Kavanagh and Riseborough, 2010; Yager, 2010). Some short term relief has resulted from the global economic recession while efforts are being made by utility companies to add more generating capacity.

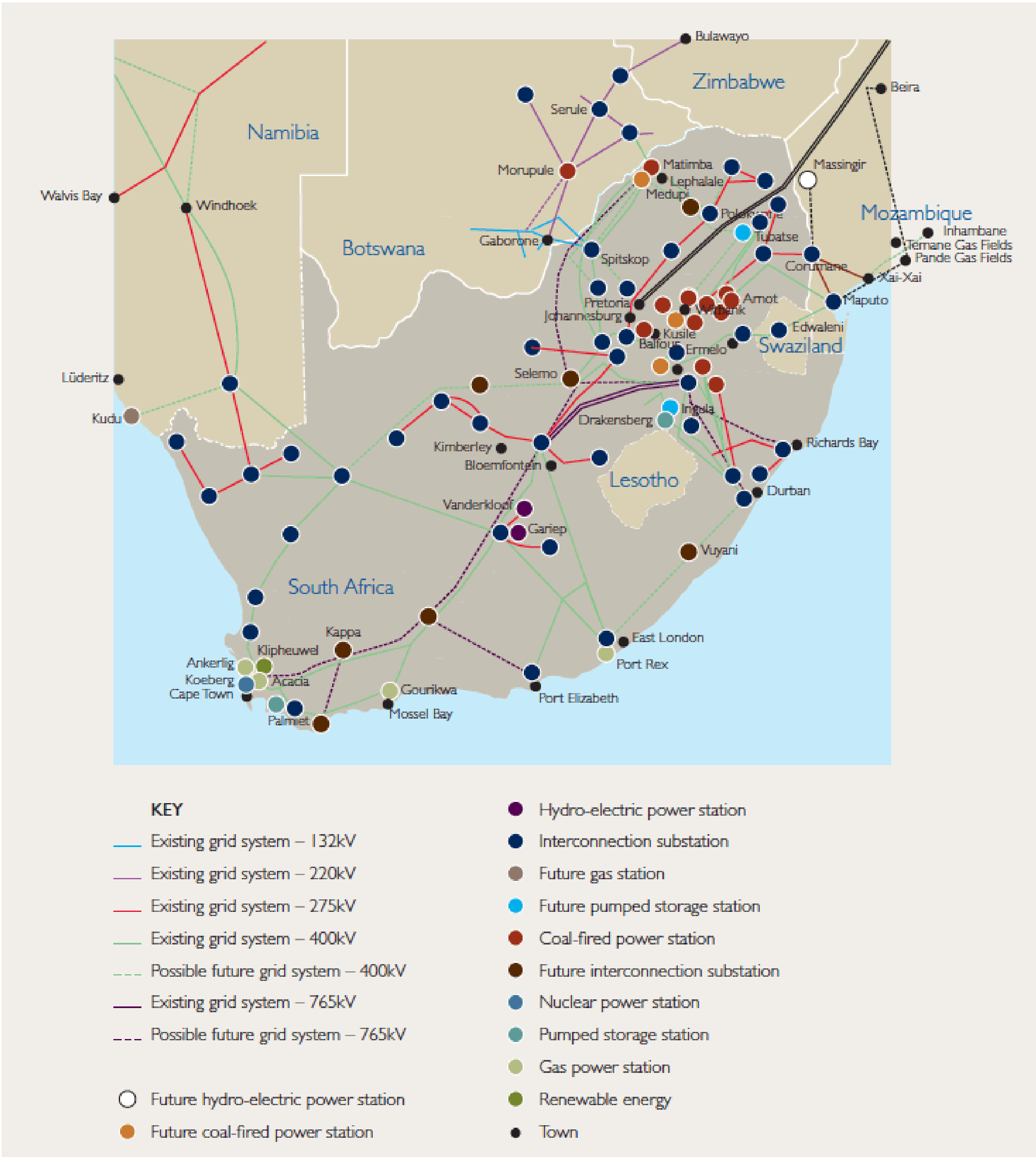

Figure 1. Map showing Eskom's southern Africa power grid map for fiscal year 2010. The figure illustrates the company's current and planned electricity distribution, generation, and other details (Eskom, 2010).

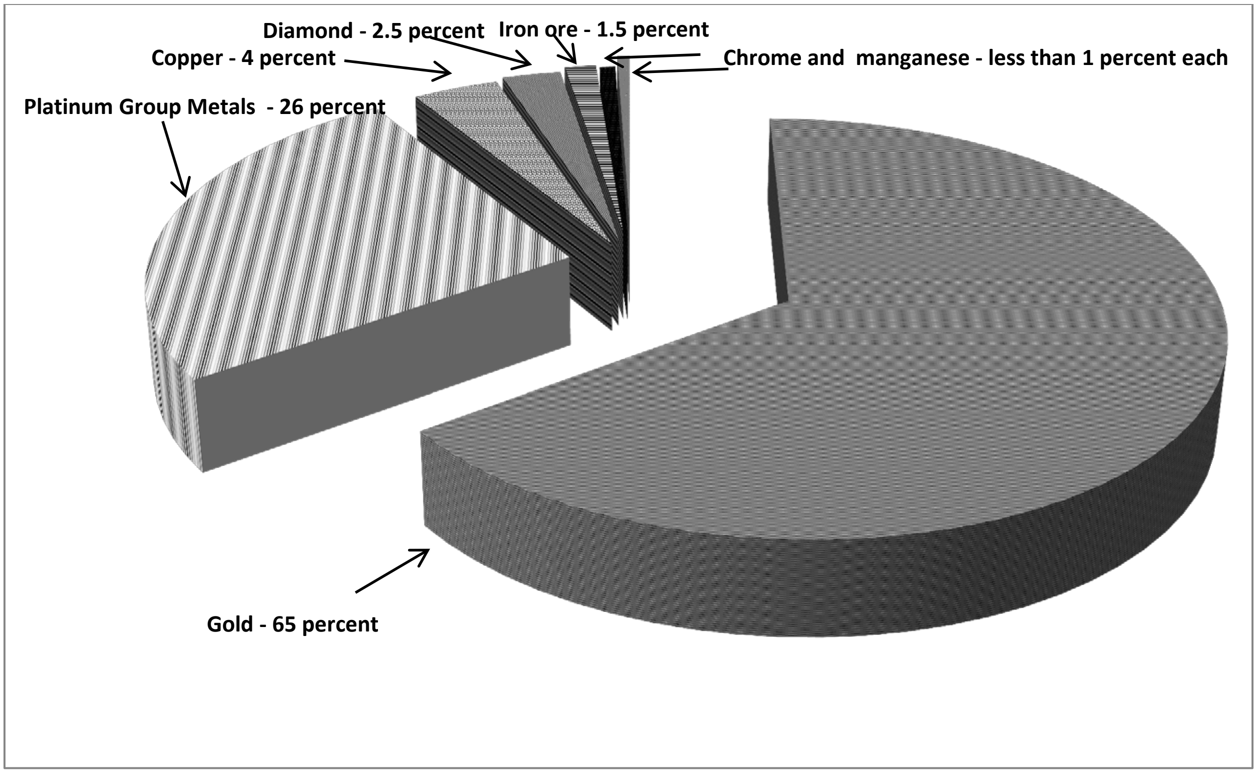

Figure 2. Estimated distribution of 26 TWh of electricity consumption during 2005 among selected mineral commodity industries in South Africa (modified from Hughes and others, 2006).

Electricity Requirements for Selected Mineral Prospects Anticipated to Start Production by 2019

Data pertaining to 183 mineral properties undergoing significant exploration activity in sub-Saharan Africa were examined to determine their potential to initiate production by the year 2019. Selection criteria included ongoing or imminent construction, acquisition of capital for development, the amount of capital expended, findings from exploration activities, and other data published in annual reports, prospectuses, and press releases. One hundred and thirty one sites were selected using these and other factors and a rough estimate of the amount of electricity required to support the announced or estimated capacity was developed for each of the potential producers. A list of the countries and the number of sites within each country are listed in table 3 and a brief discussion of South African and Ghanaian sites follows.

South Africa

Based on a review of approximately 60 sites in South Africa being explored for minerals in 2010, it was estimated that roughly 6,900 GWh will be consumed by 33 mining sites and facilities anticipated to come on-line by 2019 in South Africa. The largest portion of the future consumption will be for the production of precious metals (gold and platinum-group metals). The additional consumption will replace electricity used by sites that will shut down during that time period, complement expansions at operating mining-related facilities, and will likely be served by the addition of new generating facilities. These complexities prevented an estimate of net change in electricity consumption by the South African minerals industry by 2019.

Ghana

Electricity consumption estimates were developed for producing gold operations and bauxite mines and alumina-aluminum plants in Ghana. Based on the operations listed in tables 4, 5 and 6, it was calculated that roughly 1,700 GWh were consumed in 2010. Approximately 720 GWh could be required by gold operations anticipated to begin production by 2019. In 2010, the Gahnaian bauxite for export operation was a relatively small consumer of electricity (approximately 2.8 GWh); however, that could change if the refining and smelting sector is revitalized, which could consume roughly 3,100 GWh annually. Additions to the country's electricity generating capacity are planned through new power plants and expansions and rehabilitation of existing plants (Mingle, 2010; Top China ADR Portal, 2010).

Table 2. A compilation of estimated net generation of electricity in gigawatt hours (GWh) for selected sub-Saharan African countries in 2008. The United States is included for the purpose of comparison. Net generation does not take into account losses in transmission and distribution prior to consumption by users. Losses can exceed 20 percent. For some countries, electricity consumption exceeds domestic generation because electricity is imported from other countries, primarily South Africa.

Country name	Net GWh electricity generation, 2008	Percentage share of selected African countries (rounded to nearest whole percent, except when less than 0.5
Angola	3,940	1
Benin	130	<0.5
Botswana	590	<0.5
Burkina Faso	590	<0.5
Burundi	210	<0.5
Cameroon	5,420	<0.5
Cape Verde	260	<0.5
Central African Republic	160	<0.5
Chad	100	<0.5
Republic of the Congo (Brazzaville)	450	<0.5
Democratic Republic of the Congo (Kinshasa)	7,450	2
Côte d'Ivoire	5,550	2
Equatorial Guinea	90	<0.5
Eritrea	270	<0.5
Ethiopia	3,720	1
Gabon	1,960	1
Gambia	220	<0.5
Ghana	8,170	2
Guinea	920	<0.5
Guinea-Bissau	70	<0.5
Kenya	6,790	2
Lesotho	200	<0.5
Liberia	340	<0.5
Madagascar	1,110	<0.5
Malawi	1,680	1

Table 2. A compilation of estimated net generation of electricity in gigawatt hours (GWh) for selected sub-Saharan African countries in 2008. The United States is included for the purpose of comparison. Net generation does not take into account losses in transmission and distribution prior to consumption by users. Losses can exceed 20 percent. For some countries, electricity consumption exceeds domestic generation because electricity is imported from other countries, primarily South Africa.—Continued

Country name	Net GWh electricity generation, 2008	Percentage share of selected African countries (rounded to nearest whole percent, except when less than 0.5
Mali	490	<0.5
Mauritania	550	<0.5
Mozambique	14,980	4
Namibia	2,200	1
Niger	200	<0.5
Nigeria	20,130	6
Rwanda	160	<0.5
Sao Tome and Principe	40	<0.5
Senegal	2,230	1
Seychelles	260	<0.5
Sierra Leone	60	<0.5
Somalia	320	<0.5
South Africa	**238,300**	**66**
Swaziland	470	<0.5
Tanzania	4,280	1
Togo	160	<0.5
Uganda	2,180	1
Zambia	9,600	3
Zimbabwe	7,720	2
United States	4,119,390	N/A
Total w/o United States	**354,720**	**N/A**

Table 3. Number of sites and estimated annual electricity consumption for mines and facilities considered likely to come into production by 2019 in countries comprising sub-Saharan Africa.
[GWh, gigawatt hour]

Country	Number of sites analyzed	Estimated annual consumption, (GWh)[1,2,3]
Angola	3	24
Botswana	5	260
Burkina Faso	4	550
Cameroon	2	560
Central African Republic	2	190
Republic of the Congo (Brazzaville)	1	250
Cote d'Ivoire	3	320
Democratic Republic of the Congo (Kinshasa)	13	5,600
Eritrea	3	280
Gabon	2	480
Ghana	7	720
Guinea	2	1,500
Kenya	1	100
Lesotho	3	210
Liberia	3	500
Madagascar	1	670
Malawi	2	80
Mali	2	360
Mauritania	2	530
Mozambique	3	160
Namibia	7	780
Niger	2	290
Senegal	4	790
Sierra Leone	4	870
South Africa	33	6,900
Tanzania	4	440
Zambia	10	2,400
Zimbabwe	3	260
Total	131[4]	26,000

[1] One GWh is equivalent to 1 million kilowatt hours (kWh).

[2] Individual values and total are rounded to two significant figures.

[3] Unless otherwise stated in data, concentrates were assumed to be smelted and/or refined in country. For additional assumptions and criteria used for estimations see page 2.

[4] A total of 183 properties in sub-Saharan Africa were considered for analysis and 131 were selected.

References to Table 3

AfDevInfo, 2010, Power infrastructures in southern Africa: last accessed December 13, 2010, at *http://www.afdevinfo.com/htmlreports/vs33.html*.

Briceño-Garmendia, Cecilia, Smits, Karlis, and Foster, Vivien, 2008, Financing public infrastructure in sub-Saharan Africa—Patterns and emerging issues: The International Bank for Reconstruction and Development, The World Bank, last accessed December 13, 2010, at *www.infrastructureafrica.org/system/files/BP15_xctry_annex.pdf*.

Eskom Holdings Ltd., 2010, Eskom Holdings Limited—Integrated report: last accessed December 13, 2010, at *http://www.eskom.co.za/annreport10/index.htm*.

Hassan, E.Y., 2007, Energy management in the extractive industry—Ghana: last accessed December 13, 2010, at *http://tu-freiberg.de/fakult6/imre/contentdocuments/1228306681_03.11.2008_Energy%20Management%20in%20the%20Extractive%20Industry%20-20Ghana_Edmund%20Yaw%20Hassan.pdf*.

Hughes, A., Howells, M.I., Trikam, A., Kenny, A.R., and van Es D., 2006, A study of demand side management potential in South African industries: last accessed February 17, 2011, at *http://active.cput.ac.za/energy/web/icue/papers/2006/22_A_Hughes.pdf*.

Kaseke, Nyasha, 2010, The cost of power outages in Zimbabwe's mining sector: The African Executive, Issue 277, last accessed December 16, 2010, at *http://www.africanexecutive.com/downloads/ZIMBABWE%20MINING%20SECTOR.pdf*.

Kavanagh, M.J., and Riseborough, Jesse, 2010, Congo say talks with BHP Billiton on Inga 3 power plant are very advanced, last accessed December 16, 2010, at *http://www.bloomberg.com/news/2010-10-27/congo-says-talks-with-bhp-on-building-inga-3-very-advanced-.html*.

Mingle, Edmund, 2010, China to invest $1.2 billion in alumina refinery plant in Ghana: The Ghanaian Times, last accessed December 16, 2010, at *http://www.newtimes.com.gh/story/2360,%20http://allafrica.com/stories/201009230792.html*.

Top China ADR Portal, 2010, Bonsai [sic] Minerals to make big Ghana investment, last accessed December 16, 2010: last accessed at *http://www.chinavestor.com/knowledge-base/economy/72361-bonsai-minerals-to-make-big-ghana-investment.html*.

Trinity Power Guide, 2010, Africa power guide: last accessed December 11, 2010, at *http://www.africapowerguide.com/page.php?page=countries&compare=7*.

University of Ghana, 2005, Guide to electrical power in Ghana, First edition: Resource Center for Energy Economics and Regulation; Institute of Statistical, Social, and Economic Research, last accessed December 11, 2010, at *http://www.beg.utexas.edu/energyecon/IDA/USAID/RC/Guide_to_Electric%20Power_in_Ghana.pdf*.

U.S. Energy Information Administration, 2010, Country Energy Profiles: last accessed September 11, 2010, at *http://www.eia.doe.gov/country/index.cfm*.

U.S. International Trade Commission, 2009, Sub-Saharan Africa—Effects of infrastructure conditions on export competitiveness, Third Annual Report: Investigation No. 332-477, Publication 4071, 195 p., last accessed December 9, 2010, at *http://www.usitc.gov/publications/332/pub4071.pdf*.

Yager, T.R., 2010, The Mineral industry of Congo (Kinshasa), in Area Reports— International—Africa and the Middle East: U.S. Geological Survey Minerals Yearbook 2008, v. III, p11.1–11.9, last accessed December 9, 2010, at *http://minerals.usgs.gov/minerals/pubs/country/2008/myb3-2008-cg.pdf*.

Table 4. Electricity consumption estimate for mining and processing bauxite for export in Ghana.

[t, metric ton; kWh/t, kilowatt hours per metric ton; Gwh, gigawatt hours]

Name of site	Majority owner/operators	Mine type	Average annual ore production 2007–2010 (t)[1]	Estimated kWh/t bauxite[2]	Estimated annual electricity consumption based on average annual production 2004–2009 (GWh)[2]
Awaso Bauxite Mine	Bosai Minerals Group (80 percent), Government of Ghana (20 percent)	Surface	700,000	4	2.8

[1] Ghana exported 498,000 t of bauxite in 2004; 607,000 t in 2005; 842,000 t in 2006; 748,000 t in 2007; 700,000 t in 2008; and 440,000 t in 2009. Average annual bauxite production from 2004–2009 was 640,000 t and, for purposes of analyses, was rounded to 700,000 t. The Bosai Minerals Group has stated in a series of press releases that they intend to invest (U.S.$) 1.2 billion to rebuild the bauxite-aluminum industry in Ghana and supply funding to upgrade existing and construct new electricity supply for this and other investments. As part of the investment, Bosai intends to increase bauxite production to 1.5Mt/yr (million metric tons per year) by 2014. (Top China ADR Portal, 2010; Mingle, 2010).

[2] Bauxite ore in Ghana is extracted with front-end loaders and trucks (very large capacity mines in other countries may, in addition to front-end loaders and trucks, use electrically-powered draglines and wheel excavators and loaders to move overburden and ore), screened, crushed, washed, solar dried (less than 1 kWh/t is required to run motors if rotary driers are used), and shipped. On average, the amount of electricity used in mining bauxite is generally less than 1 kWh/t of ore because ore and overburden are drilled and blasted, and removed with diesel-powered shovels and trucks. Approximately 1 kWh/t is required for operating draglines that are used for removing either overburden or ore. Electricity used to power pumps and other in-pit equipment is usually met with the use of diesel-powered generators. The estimate of 3 kWh/t of bauxite and the annual bauxite production estimate are based on washing, screening, and crushing to minus 4 inch (100mm) size, of which roughly 2 kWh/t is required for crushing. Crushing to perhaps 200 mm would require considerably less motor power, at about 1 kWh/t bauxite (Liming Heavy Industry, 2008). Shops and administrative electricity consumption is slightly less than 1 kWh/t on a bauxite basis. Conveyor belts are used at some mines to transport bauxite from a mine to a port or alumina refinery. Belts generally consume from about 1 kWh/t for transport of several hundred meters to 5 kWh/t for moving bauxite about 50 km (ABB, 2010; FlSmidth, 2009; Tech-A Ltd., 2010; World Port Development, 2010). The range is due to factors such as distance, changes in elevation, speed, weight of material transported, and efficiency of use. Some conveyor belts are designed with generators that produce significant amounts of electricity when going downhill, thereby offsetting some of the facility's requirements and, in some cases, resulting in a net gain.

Table 5. Estimated unit and annual electricity consumption for an alumina-aluminum facility in Ghana.
[kWh/t, kilowatt hours per metric ton; Gwh/yr, gigawatt hours per year]

Name of Site	Majority owner/operator	Aluminum production 2007–2009[1]	Annual aluminum design capacity	Estimated kWh/t aluminum at capacity[2]	Total estimated annual electricity consumption at capacity (GWh/yr)[3]
VALCO[4]	Gov't of Ghana	0	200,000	15,500	3,100

[1] The highest annual aluminum production achieved since 1985 was in 1992 (180,000 t). Annual production began a significant decline from 1994 through 2002, when production dropped from 141,000 to 117,000 t. The plant has operated intermittently, producing 16,000 t in 2003; 13,000 t in 2005; and 8,000 t in 2006. There was no reported production for 2004 and 2007–2010.

[2] Includes mining, ore preparation, refining, and smelting.

[3] Estimate based on previously published capacity data, although plant is currently on care and maintenance and its condition is not known. The estimate in table 5 includes electricity used in a smelter. If processing of bauxite to alumina (400,000 t/yr alumina) is undertaken, roughly 120 GWh/yr of electricity would be consumed using the Bayer process. Bosai intends to invest into energy production if the construction of a refinery is initiated to assist in providing sufficient power for the plant and other income generating activities in the western region of Ghana.

[4] The VALCO (Volta Aluminum Company) site is on care and maintenance. Bosai has stated that they are committed to re-establish an alumina refinery by 2014, but little has been published concerning an aluminum smelter. No information was encountered concerning the proposed alumina capacity or possible aluminum capacity.

References for Table 5

ABB, 2010, Case note—ACS 1000 variable speed drives reduce downtime and increase conveying capacity of bauxite mine: last accessed March 30, 2011, at *http://www05.abb.com/global/scot/scot216.nsf/veritydisplay/d9cb193984a6dca9c12577e400563940/$file/worsley%20conveyor%20revb_lowres.pdf*.

Adusu, Christian, 2010, International—China's new deal for Ghana and the lessons: Modrnghanaweb, last accessed November 13, 2010, at *http://modrnghanaweb.com/international-china-s-new-deal-for-ghana-and-the-lessons-147937.htm*.

Bhpbilliton, 2007, Aluminum-Customer sector group: Sustainable development report 2005–2006, last accessed January 28, 2011, at *http://www.bhpbilliton.com/bbContentRepository/aluminiumsustainabilityreport.pdf*.

Burns, Stuart, 2009, Power costs in the production of primary aluminum: last accessed January 20, 2011 at *http://agmetalminer.com/2009/02/26/power-costs-in-the-production-of-primary-aluminum/*.

FLSmidth A/S, 2009, Boddington Gold Mine gets 11.5 kilometers of conveyor belt: last accessed March 30, 2011, at *http://www.flsmidth.com/en-us/eHighlights/Archive/Minerals/2009/December/Boddington+Gold+Mine+gets+11+kilometres+of+conveyor+belt*.

GhanaWeb, 2010, Ghana's "integrated aluminum" fever: last accessed November 13, 2010, at *http://www.ghanaweb.com/GhanaHomePage/NewsArchive/artikel.php?ID=176324*.

Knapp, Ron, 2009, Aluminum: Presentation by Ron Knapp, International Aluminum Institute, to the International Energy Agency, Industry Expert Review Workshop, Paris, France, February 9–10, 2009, last accessed on August 18, 2010, at the International Aluminum Institute Web site *http://www.iea.org/work/2009/industry_expert/knapp.pdf*.

Light Metal Age, 2010, Primary aluminum smelters of the world: last accessed August 16, 2010, at *http://www.lightmetalage.com/producers_primary.php*.

Liming Heavy Industry, 2008, Liming Heavy Industry web site: last accessed January 28, 2011 at *http://www.shcrusher.com/*.

Mingle, Edmund, 2010, China to invest $1.2 billion in alumina refinery plant in Ghana: The Ghanaian Times, last accessed December 13, 2010, at *http://www.newtimes.com.gh/story/2360,%20http://allafrica.com/stories/201009230792.html*.

Shriber, Todd, 2010, Bonsai [sic] Minerals to make big Ghana investment: Chinavestor, last accessed December 13, 2010, at *http://www.chinavestor.com/knowledge-base/economy/72361-bonsai-minerals-to-make-big-ghana-investment.html*.

Tech-A Limited, 2010, Engineering consultancy projects: last accessed March 30, 2011, at *http://www.tech-a.com/Assistance/projects.htm*.

Turkson, J.K. and Amadu, M.B., 1999, Environmental protection implications of the electric power restructuring in Ghana: Working paper presented to the UNEP Collaborating Center on Energy and Environment, Riso National Laboratory, Roskilde, Denmark, September, 1999, last accessed August 16, 2010, at the United Nations Environmental Programme Web site *http://uneprisoe.org/Workpapers/w[a[er8.pdf*.

Volta River Authority, 2007, Overview of the energy sector in sub-region and the roles of natural gas—Ghana case study: last accessed August 16, 2010, at *http://www.beg.utexas.edu/energyecon/accra_july_07_workshop/VRA_Overview%20of%20the%20energy%20sectors%20in%20the%20sub-region.pdf*.

World Port Development, 2010, Conveyor systems makers transfixed by the "R" word: last accessed March, 30, 2011, at *http://www.worldportdevelopment.com/index.php?option=com_content&view=article&id=217%3Aconveyor-systems-makers-transfixed-by-the-r-word&Itemid=434*.

Table 6. Estimated electricity requirements for selected operating and prospective gold operations in Ghana.
[kwh, kilowatt hours; Gwh/yr, gigawatt hours per year]

Name of site	Majority owner/operator	Mine type[1]	Gold recovery technology[2]	Estimated annual refined gold production capacity (ounces)	Estimated kWh/ounce gold produced for mining and processing at estimated production capacity in 2010[3]	Total estimated annual electricity consumption (GWh/yr)[3]	Grid (T, P)[4,5]
Ahafo	Newmont Ghana Gold Ltd.	S	CIL	520,000	550	286	P
Bogoso/Prestea[6]	Golden Star Resources Group	S	CIL	200,000	600	120	P
Chirano[7]	Kinross	C	CIL	250,000	900	225	T
Damang	Gold Fields Ghana Ltd.	S	CIL	220,000	600	132	P
Iduapriem	AngloGold Ashanti	S	CIP[8]	230,000	550	127	P
Obuasi	AngloGold Ashanti	(90 %. U, 10 % S and T)	Flotation, gravity, and CIL	380,000	Surface (400), UG (1,300 kWh) weighted average = 1,200 kWh[9]	456	P
Tarkwa	Gold Fields Ghana Ltd.	S	CIL, CIP[10]	750,000	300	225	P
Wassa	Golden Star Resources Group	S	CIL	220,000	600	132	P
Total of producing operations	**N/A**	**N/A**	**N/A**	**2,770,000**	**N/A**	**1,700[11]**	**N/A**
Non-producing properties w/ favorable economics and possible production within next 5 years.[12]	**N/A**	C	CIL	1,100,000	600	700	N/A
Total of producers and nonproducing properties.	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**2,400**	**N/A**

[1] Surface open pit (S) or combined open pit-underground (C), tailings (T).

[2] Carbon-in-leach (CIL), Carbon-in-pulp (CIP).

[3] kWh—kilowatt hour, GWh—Gigawatthours (equal to 1 million kilowatt hours). Estimates rounded to two significant figures.

[4] P—Partially grid dependent to meet electricity requirements to operate at capacity, T—Total grid dependent to meet gold production capacity requirements. All operations are equipped with back-up generators to supply electricity for critical requirements that can include compressors, hoists, pumping, ventilation, and other equipment.

[5] An 80 MW diesel-powered electricity plant was constructed in 2007 and provides all or supplemental electricity to the gold operations of Gold Fields Ghana Ltd., Anglo Gold Ashanti Ltd., Newmont Ghana Gold Ltd., and Golden Star Resources Ltd. Based on the partnership, each receives 20MW of electricity. The plant is also connected to the grid.

[6] Underground mining currently inactive.

[7] Estimate for Chirano includes surface and underground mining. The facility is undergoing modification. If production is restricted to surface mining, electricity consumption would be approximately 550 kWh/ounce of gold, but combined operations are likely.

[8] Heap leach discontinued.

[9] Obuasi underground requires refrigerated ventilation and has multiple shafts. Employs 5,000 people.

[10] Approximately 70 percent of the mined ore is milled and treated using CIP, 30 percent of the ore is processed by CIL.

[11] At least 700 GWh are provided by private company-owned generation. See footnote 8.

[12] Includes Bibiani, a past producer, and six well-explored and developing properties (Akyem, Ayanfuri, Grumesa, Kubi, Nzema, and Wa) with a combined potential production of approximately 1.1 million ounces of gold per year within the next 5 years, assuming favorable economics and other critical factors. They will not likely begin operations at the same time.

References for Table 6

AngloGold Ashanti Ltd., 2010, AngloGold Ashanti Mineral Resource and ore reserve report 2009: last accessed November 7, 2010, at *http://www.anglogold.com/subwebs/InformationForInvestors/Reports09/AnnualReport09/f/AGA_RR09.pd*.

AngloGold Ashanti Ltd., 2010, Sustainability review—Year in review: last accessed November 7, 2010, at *http://www.anglogold.com/subwebs/InformationForInvestors/Reports09/AnnualReport09/review_gh.htm*.

AngloGold Ashanti Ltd., 2010, AngloGold Ashanti Abridged report—Building a strong foundation: accessed November 7, 2010, at *http://www.anglogold.com/subwebs/InformationForInvestors/Reports09/AnnualReport09/f/AGA_ABRIDGED09.pdf*.

Bowers, Emily, 2009, Newmont to decide on second Ghana gold mine in 2010: The Ghanian Journal, last accessed November 7, 2010, at *http://www.theghanaianjournal.com/2009/12/10/newmont-to-decide-on-second-ghana-gold-mine-in-2010/*.

Business Wire, 2008, Golden Star reports increases in power costs in Ghana: last accessed November 7, 2010, at *http://www.allbusiness.com/energy-utilities/utilities-industry-electric-powerity/11388608-1.html*.

Emery, Julian, 2010, West African gold sector—growth and merger opportunities: Ambrian Metals and Mining, 11 March 2010, last accessed November 7, 2010, at *http://www.adamusresources.com.au/files/10-03%20Ambrian%20-%20West%20Africa%20Gold%20Sector%20-%20March%202010.pdf*.

Gold Fields, Ltd., 2010, Sustainable development—securing the future: last accessed November 7, 2010, at *http://www.goldfields.co.za/index.php*.

Gold Fields Ltd., 2010, Damang Gold Mine-Overview—Realising the dream of 2025 and beyond: last accessed November 9, 2010, at *http://www.goldfields.co.za/presentations/2010/damang_overview_19052010.pdf*.

Golden Star Resources Ltd., 2011, Golden Star Resources website: last accessed November 7, 2010, at *http://www.gsr.com/Operations/Wassa.asp*.

Hassan, E.Y., 2008, Torkornoo and Associates Limited (TAL)—Energy management in the extractive industry—Ghana: last accessed November 9, 2010, at *http://tu-freiberg.de/fakult6/imre/contentdocuments/1228306681_03.11.2008_Energy%20Management%20in%20the%20Extractive%20Industry%20-%20Ghana_Edmund%20Yaw%20Hassan.pdf*.

Hill, Liezel, 2009, Newmont sees positive short-term outlook for Ghana power supply: last accessed November 9, 2010, at *http://www.miningweekly.com/article/newmont-sees-positive-short-term-outlook-for-ghana-power-supply-2009-06-30*.

Kinross Gold Corporation, 2010, Chirano, Ghana: last accessed November 13, 2010, at *http://www.kinross.com/operations/operation-chirano-ghana.aspx.*

KITCO, 2010, Gold mine production costs: last accessed November 13, 2010, at *https://www.kitcomm.com/showthread.php?t=63165%20%20Gold%20mines%20production%20Costs-Kitco%20Forum*.

Lesova, Polya, 2008, South Africa Raises electricity prices by 27.5%: Market Watch, last accessed November 13, 2010, at *http://www.marketwatch.com/story/south-africa-raises-electricity-prices-by-275*.

Redback Mining Inc., 2008, A growing producer in Africa: last accessed November 13, 2010, at *http://www.redbackmining.com/i/pdf/FactSheet.pdf*.

Appendix 1. Electricity Requirements for the Production of Selected Mineral Commodities

Table 7. (*A*) Generalized electricity requirements for mining and producing aggregate (crushed rock).[1]
[kWh/t, kilowatt hours per metric ton]

Process	Feedstock[1]	Specific electricity usage (kWh/t product)
Mining		
Surface mining using drills, trucks, and non-electric shovels	Primarily limestone, dolomite, granite, and sandstone.	--[2]
Generalized processing technology (sizing)[3]		
Crushed, screened, and stacked	Limestone	1.5
Crushed, screened, and stacked	Well-fractured andesite	1–2
Crushed, screened, and stacked	Basalt	2–4
Crushed to minus 2- inch sized material, and screened	Not specified	2.5
Crushed to 20 mm (3/4 inch), screened and stacked	Not specified	3–4
Crushed to sand size (unspecified), screened, and stacked	Not specified	4–5

[1] Limestone, dolomite, and granite comprise over 75 percent of the U.S. crushed stone production.

[2] Mining in quarries using trucks, shovels, and other equipment consumes very little electricity/t of production, except for what might be used for dewatering, lighting, and in maintenance shops. The total probably amounts to less than 0.25 kWh/t.

[3] Quarried rock may or may not include one or more of the following: crushers, conveyor belts, vibrating tables, screens, cyclones, clarifiers, stackers, and other equipment that consume electricity. In general, the crusher consumes the largest portion of electricity per t at a full integrated crushed stone operation that produces a minus 2-inch product (30 percent), followed, in descending order, by conveyors (18 percent), screens (13 percent), and pumps (12 percent). Most of the balance of electricity requirements resides roughly equally in the asphalt plant, dust collection, sand plant, and lights (Moray and others, 2006). Also, plants may or may not be tapped into the grid because of their remoteness. In many cases, they generate their own power in part or in whole using diesel-powered generators.

References for Table 7*A*

Adel, Greg, Kojovic, Toni, and Thornton, Darren, 2006, Mine-to-mill optimization of aggregate production: last accessed September 19, 2010, at *http://www.osti.gov/bridge/purl.cover.jsp?purl=/914568-TIDTd7/.*

Akashganga, 2010, Increase your profitability by installing VSI crusher: last accessed September 19, 2010, at *http://www.crushedsand.com/vsi_crusher.html.*

Miningbasics.com, 2010, Crusher operating costs: last accessed September 19, 2010, at *http://www.miningbasics.com/crusher-operating-costs.*

Missouri Department of Natural Resources, 2010, Strack Excavating L.L.C., Mining permit application: last accessed September 19, 2010, at *http://dnr.mo.gov/env/apcp/docs/Strack%20Excavating%20Air%20Permit%20Application%202010-07-057.pdf.*

Moray, Satyen, Throop, Nathan, Seryak, John, Schmidt, Chris, Fisher, Chris, and D′Antonio, Mark, 2006, Energy efficiency opportunities in the stone and asphalt industry, in Twenty-Eighth Industrial Energy Technology Conference, proceedings: New Orleans, La, Proceedings of the Twenty-Eighth Industrial Energy Technology Conference, last accessed September 19, 2010, at *http://repository.tamu.edu/bitstream/handle/1969.1/5644/ESL-IE-06-05-27.pdf?sequence=4.*

Table 7. (*B*) Generalized electricity requirements for mining and processing unconsolidated sand and gravel for construction.

[kWh/t, kilowatt hour per metric ton]

Process	Feedstock	Specific electricity usage (kWh/t product)
	Mining	
Cutterhead suction dredge[1]	Subaqueous sand and gravel	1
Surface mining using trucks and shovels	Sand and gravel	--[2]
	Generalized processing[3]	
Sorting, screening, and stacking without crushing	Sand and gravel	1.0
Sorting, screening, and stacking with 25 percent crushed to minus ¾ inch	Sand and gravel	1–2
Sand and gravel sized material	Sand and gravel	7[4]
Total mining and processing FOB site	**Sand and gravel**	**1–7**[5]

[1] Cutterhead suction dredges are the most common type of floating electric suction dredge in commercial use for offshore or "pond" sand and gravel mining. The electricity/unit recovered will change owing to economies of scale and other factors related to productivity. The kWh estimate is based on 10–15.2 meter maximum digging depth and removing 460 cubic meters/hour (920 t/hr) of material. Tonnage is based on a weight of 2 t per cubic meter of wet sand and gravel. Calculations are rounded to one significant figure. Plants may or may not be tapped into the grid because of their remoteness or other reason. They generate their own power in part or in whole on the barge, adjacent to the barge, or on land.

[2] Mining sand and gravel using trucks and shovels uses very little electricity/t of production except for what might be used for dewatering, lighting, and in the maintenance shop. The total is less than 0.25 kWh/t in the great majority of cases.

[3] Processing of sand and gravel plants may or may not include one or more of the following: crushing (to varying extents depending on feedstock size and desired material sizes), conveyor belts, vibrating tables, screens, cyclones, clarifiers, stackers, lighting, dust control, compressors, and other equipment that consume electricity. Crushing material to meet specifications can increase electricity consumption significantly. Plants may or may not be tapped into the grid because of their remoteness. They generate their own power in part or in whole.

[4] Presented as an example of a high electrical energy consumptive operation in the sand and gravel industry. The relatively small facility is located in Germany with an annual capacity of 150,000 t (Lahmeyer International, 2006). Estimates for most unconsolidated sand and gravel operations consume significantly less electricity per unit of production.

[5] Based on the 1997 census performed by the U.S. Census Bureau, approximately 5.2 kWh/t was required to produce approximately 500 million t of sand and gravel from 2,334 mining operations in 1997 in the United States. The estimate includes a mix of operations, but is heavily weighted towards production from unconsolidated construction sand and gravel surface operations.

References for Table 7*B*

Dredging Today, 2010, Significant dredgers of 2010: last accessed September 20, 2010, at *http://www.worldmaritimenews.com/article/Dredging/16231/significant+dredgers+of+2010*.

Ellicott Dredges, LLC, 2010, Ellicott dredge equipment and specifications: last accessed September 20, 2010, at *http://webcache.googleusercontent.com/search?q=cache:q0Wv-fqGNqMJ:www.dredge.com/dredge-*.

Lahmeyer International, 2006, Audit in the energy intensive industrial branch—Sand & gravel mining and processing: last accessed September 20, 2010, at *http://www.lahmeyer.de/en/projects/details/project/252/.*

Moray, Satyen, Throop, Nathan, Seryak, John, Schmidt, Chris, Fisher, Chris, and D′Antonio, Mark, 2006, Energy efficiency opportunities in the stone and asphalt industry, in Twenty-Eighth Industrial Energy Technology Conference, New Orleans, LA, 2006, Proceedings: last accessed September 20, 2010, at *http://repository.tamu.edu/bitstream/handle/1969.1/5644/ESL-IE-06-05-27.pdf?sequence=4.*

Shasta County, California Resources Management, 2010, Shasta Ranch excavation and mining plan: last accessed September 20, 2010, at *http://www.co.shasta.ca.us/departments/resourcemgmt/drm/Shasta%20Ranch/Ch%204-Excavation%20and%20Mining%20Plan.pdf*.

U.S. Census Bureau, 1999, Construction sand and gravel mining—1997: U.S. Department of Commerce, Economics and Statistics Administration, last accessed April 6, 2011, at *http://www.census.gov/prod/ec97/97n2123e.pdf*.

Table 7. (*C*) Estimated electricity requirements for the production of aluminum from bauxite ore.

[t, metric ton; kWh/t, kilowatt hour per metric ton]

Country/site name	Estimated annual capacity, (1000 t)	Specific electricity usage, (kWh/t Al)
Cameroon		
Edea	100	19,500
Ghana		
Tema,	200	16,050
Mozambique		
Maputo, Mozal	562	11,560
South Africa[1,2]		
Richards Bay-Bayside	195	13,000
Richards Bay-Hillside	710	--
All Africa[3]	1,970	14,600

[1] In addition to the existing plants identified above, there are suspended plans to construct a 720,000 t aluminum smelter at Port Elizabeth, South Africa. If the plant is constructed and comes on-line with those currently operating, it would increase the electricity demand for full-capacity aluminum smelting in sub-Saharan Africa from 3.3 to 4.2 GW.

[2] The increased cost of electricity and interruptions coupled with limited supply have incentivized producers to reduce electricity consumption through modernization, replace older and less-efficient pot lines, and install onsite generation facilities.

[3] Average electricity consumption estimated by the International Aluminum Institute. Using an average electricity requirement of 14,600 kWh for producing one t of aluminum in a smelter at full capacity for plants in Africa would result in a total annual electricity consumption of 28.6 terrawatt hours. Considerably more power would need to be generated to accommodate losses of electricity through transmission, transformers, and other losses occurring prior to the point of consumption.

References for Table 7*C*

Aussel, Jean-Paul, Frison, Jean-Claude, and Kroutz, Shaun, 1997, Commissioning of ALUSAF Hillside smelter reduction pots, in The Metallurgical Society annual meeting, 1997, Proceedings: last accessed August 18, 2010, at *http://www.tms.org/Meetings/Annual-97/Program/Sessions/TA230A.html.*

Bhpbilliton, 2007, Aluminum—Customer sector group: Sustainable development report 2005–2006, last accessed January 28, 2011, at *http://www.bhpbilliton.com/bbContentRepository/aluminiumsustainabilityreport.pdf.*

Bray, E.L., 2010, Aluminum: U.S. Geological Survey, 2008 Minerals Yearbook [Advance Release], v. I, p. 5.1–5.19, last accessed August 9, 2010, at *http://minerals.er.usgs.gov/minerals/pubs/commodity/aluminum/myb1-2008-alumi.pdf.*

Burns, Stuart, 2009, Power costs in the production of primary aluminum: last accessed January 20, 2011 at *http://agmetalminer.com/2009/02/26/power-costs-in-the-production-of-primary-aluminum/.*

Knapp, Ron, 2009, Aluminum, Presentation by Ron Knapp (International Aluminum Institute) to the International Energy Agency, Industry Expert Review Workshop, Paris, France, February 9–10, 2009: International Energy Agency, last accessed August 18, 2010, at *http://www.iea.org/work/2009/industry_expert/knapp.pdf.*

Light Metal Age, 2010, Primary aluminum smelters of the world: Light Metal Age, last accessed August 16, 2010, at *http://www.lightmetalage.com/producers_primary.php*.

Turkson, J.K., and Amadu, M.B., 1999, Environmental protection implications of the electric power restructuring in Ghana, working paper presented to the UNEP Collaborating Center on Energy and Environment, Risø National Laboratory, Roskilde, Denmark, September, 1999: United Nations Environmental Program, last accessed August 16, 2010, at *http://uneprisoe.org/Workpapers/wpaper8.pdf.*

Volta River Authority, 2007, Overview of the energy sector in sub-region and the roles of natural gas—Ghana case study: University of Texas, last accessed August 16, 2010, at *http://www.beg.utexas.edu/energyecon/accra_july_07_workshop/VRA_Overview%20of%20the%20energy%20sectors%20in%20the%20sub-region.pdf.*

West, Edward, 2010, South Africa—Load shedding curbs BHP aluminum smelters: All Africa, last accessed August 18, 2010, at *http://allafrica.com/stories/2010007050867.html*.

Table 8. Estimated electricity requirements for production of ore from a multi-million t/yr block-caving operation with an underground cone crusher and a 10-mile conveyor belt to the beneficiation plant that produces one concentrate by flotation. Approximately 99.5 percent of the plant feed reports to the tailings storage area.

[kWh/t, kilowatt hour per metric ton][1]

Product and process	Feedstock	Product	Estimated mine and beneficiation plant electricity usage (kWh/t ore)[2]
Underground block cave mining	Molybdenite ore	Molybdenite ore	12[3]
Underground crusher	Molybdenite ore	Molybdenite ore	3.4
Underground-surface belt	Molybdenite ore	Molybdenite ore	1.7
Beneficiation (primarily crush, grind, float, dry, and disposal of tailings)	Molybdenite ore	Molybdenite concentrate	17
Total	--	--	34

[1] Modeled after engineering data for the Henderson molybdenum mine.

[2] Electricity supplied by grid. Estimates rounded to two significant figures.

[3] Ventilation comprises 65 percent or 7.6 kWh/t ore of underground electricity consumption, not including the crusher or conveyor belt (see additional discussions relating to conveyor belts in table 3). Most of the balance is consumed by the use of mining equipment, providing compressed air, lighting, dewatering the mine, operating the hoists, and running the underground shops. Block-caving generally requires less ventilation per unit of ore extracted than other underground mining methods. Grinding of ore consumes the largest portion of electricity during beneficiation (fig. 3) and prepares the ore for flotation (fig. 4).

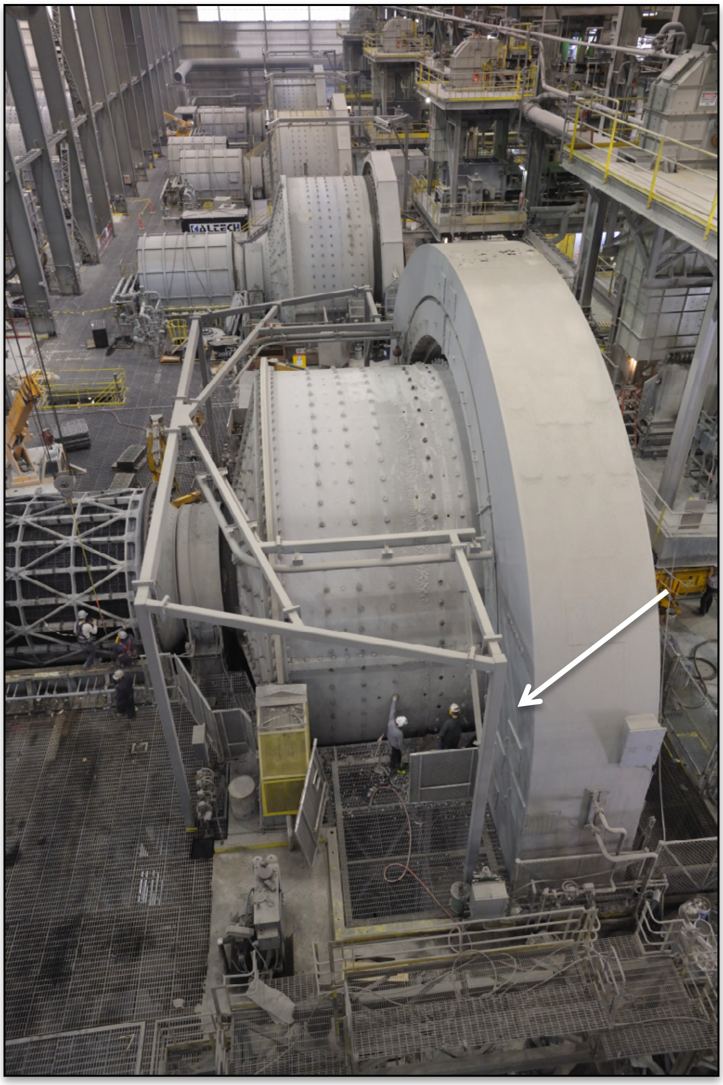

Figure 3. Large electrically-driven ball mills used for grinding ore to a size suitable as feedstock to the flotation cells. Note the two plant employees for scale, indicated by a white arrow. Photograph is provided courtesy of Rio Tinto's Bingham Kennecott Utah Copper.

Figure 4. Ground ore is directed to a series of froth flotation cells in which hydrophobic copper sulfides and other minerals attach to bubbles where they form a froth that is skimmed off. The resulting concentrate contains about 28 percent copper. Photograph is of one froth flotation cell with a volume of about 3,000 cubic feet (roughly 15 feet in width, length and depth) at the Copperton concentrator that treats ore from the Bingham Canyon pit, Utah. Concentrate is piped 27 kilometers (km) to the smelter (Brian Davis, Manager for Government and Community Relations, Rio Tinto, Utah, oral and written commun., February 16, 2011). Image is provided courtesy of Rio Tinto's Bingham Kennecott Utah Copper.

Table 9. Estimated electricity requirements for cement production.
[kWh/t, kilowatt hour per metric ton]

Region/country (site name or company)	Electricity usage (kWh/t cement)[1]
Democratic Republic of the Congo (Kinshasa)	
Cimenterie de Lukalu (CILU)	--
Cimenterie Nationale (CINAT)	122
Kenya	
Bamburi Cement Ltd.	105
EAPCC	140
Namibia	
Ohorongo Cement (Pty) Ltd.	130
South Africa	
Nonspecific	120–140
Uganda	
Bamburi Cement Ltd.	105
Athi River Mining	105
Sub-Saharan Africa, excluding South Africa	**120**
Western Europe	
Nonspecific	95–130
Japan	
Nonspecific	96–107
United States	
Wet plant	141
Dry plant	142
Grinding plant	77[2]
"Typical"	129[3]
World	
Average	110
Range	90–150

[1] Estimates of electricity requirements reflect greater or lesser efficiencies, but represent to a greater degree the grain size of the cement product. For example, the U.S. cement industry produces a high percentage of fine-grained cement resulting in higher electricity requirements for grinding. Europe experiences lower electricity requirements for cement owing to a coarser grain-sized product (Van Oss, oral commun., 2010). Also, because of their remoteness some cement plants do not have access to a utility grid and must generate their own power.

[2] Note that the grinding plant is for a sole plant that processes clinker for U.S. markets and therefore the product is finer grained than that consumed by most other world markets. In doing so, more electricity is consumed per unit.

[3] Estimated at 7kWh/t for quarrying and pre-blending, 31 kWh/t crushing and grinding, 8 kWh/t for blending, 28 kWh/t burning and cooling, 48 kWh/t for final grinding, and 7 kWh/t for conveying and packaging.

References for Table 9

Cement Plant Forum, 2011, Your specific power consumption for your OPC: last accessed May 25, 2011, at *http://www.cementplant.com/cpf/posts/list/69.page*.

Cochez, Evelien, and Nijs, Wouter, 2010, Cement production: Technology brief 103, June 2010,last accessed May 25, 2011, at *http://www.etsap.org/E-techDS/PDF/I03_cement_June%202010_GS-gct.pdf*.

Heita, Desie, 2009, N$2.5 billion cement plant taking shape: New Era—Newspaper for Namibia, last accessed August 9, 2010, at *http://www.newera.com.na/article.php?articleid=5532*.

Japan Cement Association, 2006, Specific power consumption: last accessed March 13, 2011, at *http://www.jcassoc.or.jp/cement/2eng/eh2.html*.

Krueger, Dieter, 2009, A background to major power usage areas, in Energy Efficiency Made Simple, Chapter 1.1: last accessed August 9, 2010, at *http://www.crown.co.za/resources/docs/Handbooks/EEMS-Vol-II-2009/EEMS-Handbook-2009-Chapter-1_1.pdf*.

Van Oss, H.G., 2008, U.S. Geological Survey Minerals Yearbook, Cement Chapter, Table 8: U.S. Geological Survey, last accessed August 9, 2010, at *http://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2008-cemen.pdf*.

Vleuten, Frank, van der, 1994, Cement in development—Energy and environment: Technische Universteit Eindhoven (Eindhoven University of Technology), Eindhoven, Netherlands, 152 p., last accessed August 9, 2010, at *http://alexandria.tue.nl/extra1/afstversl/E/417830.pdf*.

World Bank, 2009, Cement sector program in sub Saharan Africa: Barrier analysis to CDM and solutions, Final Report, accessed August 9, 2010, at *http://siteresources.worldbank.org/INTCARFINASS/Resources/FinalReportAfricaCementSector090420.pdf*.

Table 10. Generalized estimated electricity requirements for the production of chromite ore products (lump, chip, and fines of chemical, metallurgical, and foundry grade chromite) from underground room and pillar mining and gravity beneficiation.

[kWh/t, kilowatt hour per metric ton]

Product and process	Feedstock	Product(s)	Estimated mine and beneficiation plant electricity usage (kWh/t ore produced)[1]
Underground mining (R&P)[2]	Chromite ore	Chromite ore	20–25
Underground mining (SLC)[3]	Chromite ore	Chromite ore	48
Beneficiation (crushing, cyclones, spirals, and DMS)[4,5]	Chromite ore	Lump, chip, and fines of chemical, foundry, and metallurgical grade chromite.	15–24

[1] Estimates do not include ancillary services such as hospitals, town sites, and other facilities not directly related to the mine and beneficiation plants. Estimates are limited to the mine and beneficiation plant.

[2] Based on Mecklenburg chrome project, South Africa, using the room and pillar method (R&P). Proposed 720,000 t/yr of ore using LHDs with ore conveyed (2 belts) to surface facility through inclines. LHDs are used for mining ore with proposed depths to 400 meters. The use of LHDs and belts for extracting chromite ore from underground is somewhat typical in South Africa owing to the nature of the ore bodies' geometry. Some mines, such as Xstrata's Kroondal mine have capacities of approximately 2 million t/yr of ore.

[3] Based on the feasibility study for the proposed Voskhod mine in Kazakhstan using sublevel caving (SLC) and selective mining of metallurgical grade chromite ore

[4] The ore recovered from the mine is crushed and wet-screened. Dense media separation (DMS), cyclones, and other heavy media separation methods are employed, from which three chromite products (each with various sizes) are produced and shipped by truck. The process is somewhat typical of South African operations that do not include pelletization on site.

[5] The engineering and cost data contained in the Voskhod feasibility study are modeled on South African operations by SRK Consulting, 2006.

References for Table 10

Coffey Mining, 2007, Mecklenburg chrome project: last accessed August 12, 2010, at *http://www.chromexmining.co.uk/Projects/Mecklenburg_Project/Feasibility_Studies/Mecklenburg_Chrome_Project_-_BFS_Study_(8.35Mb)/File.aspx?id=61*.

Jacobs, James, Guertin, Jacques, and Avakian, Cynthia, (eds.), 2004, Chromium (VI) handbook: New York, CRC Press, Taylor and Francis Group, 800 p.

Mining-technology.com, 2010, Semancor chrome mines—South Africa: last accessed August 12, 2010, at *http://webcache.googleusercontent.com/search?q=cache:CB9u8ho6bekJ:www.samancorcr.com/content.asp%3FsubID%3D9+samancor+chrome+mine+energy+kwh+mine+mining&cd=1&hl=en&ct=clnk&gl=us.*

SRK Consulting, 2006, Voskhod feasibility study 43-10,1 summary technical report: last accessed August 12, 2010, at *http://www.orielresources.com/uploads/017SummaryTechReportNI43101r.pdf*.

Table 11. Estimated electricity requirements for the production of coal.
[kWh/t, kilowatt hour per metric ton][1]

Technology	Feedstock[2]	Estimated plant usage (kWh/t coal)
Mining method		
Surface[3,4]		
Surface mining w/ cable shovels (not including overburden)	Anthracitic and bituminous coal	1 (0.72–1.2)
Dragline for overburden removal at 1:1 stripping ratio	Anthracitic and bituminous coal	1.39
Dragline for overburden removal at 2:1 stripping ratio	Anthracitic and bituminous coal	2.38
Dragline for overburden removal at 3:1 stripping ratio	Anthracitic and bituminous coal	4.17
Dragline for overburden removal at 4:1 stripping ratio	Anthracitic and bituminous coal	5.56
Dragline for overburden removal at 5:1 stripping ratio	Anthracitic and bituminous coal	6.39
Surface mining, plus overburden removal with waste:ore stripping ratios of 2:1–4:1[5]	**Anthracitic and bituminous coal**	**3.38–6.56**
Underground[6]		
Illinois deep mines using room and pillar (approx. 200–300 meters depth)[7]	Bituminous	--
Mining	Bituminous	14
Hoisting	Bituminous	6.0
Pumping (dewatering)	Bituminous	2.5
Ventilation	Bituminous	2.0
Drilling	Bituminous	1.8
Break and convey	Bituminous	0.80
Ancillary services	Bituminous	0.50
Total	Bituminous	28
Various underground mining methods	**Anthracitic and bituminous coal**	**11–25**
Beneficiation method[8]		
Crushing, grinding and cleaning	Anthracitic and bituminous coal	15–30
Estimated totals for operations[9]		
Surface mine with a range of estimated stripping ratios of 2:1–4:1[5] and beneficiation	Anthracitic and bituminous coal	18–37
Underground mine and beneficiation	Anthracitic and bituminous coal	26–55

[1] Estimates of electricity requirements are generalized. U.S. data formed the basis for some of the estimates. Electricity requirements between coal operations vary considerably, owing to factors that include but are not limited to mine type (surface and underground mining methods that include longwall and shortwall, continuous and room and pillar mining, shafts or inclines), equipment choices, depth and orientation to coal, ventilation and dewatering requirements, stripping ratios, underground mine waste versus coal, economies of scale (small surface mines use hydraulic shovels, large surface mines employ electric shovels), coal type (hardness, competence), coal transport to the surface (belts, mine cars), crushing and pulverizing, cleaning and washing, and numerous other factors that can affect the production process. The availability of capital, mining methods dictated by geology and engineering, regulations, and the relationship between labor

cost and productivity are some of the major factors in determining the amount and types of mechanization that may determine electricity use. Draglines consume roughly 1.7 kWh per cubic meter of overburden. Converting these values to a t basis would require specific information on the blasting method and efficiency, rock breakability, moisture content, rock or soil type, and other factors at a particular site, but would be roughly 0.85 kWh per t assuming 2 t per cubic meter of bank or overburden material.

[2] In South Africa, approximately 47 percent of the country's coal production was reported to originate from underground operations and 63 percent from surface mines. Botswana produced about 1 million t from its only coal mine. The mine is operated as an underground operation and supplies coal to the Morupule power plant. See *http://www.infomine.com/index/properties/MORUPULE_COAL_MINE.html*, and *http://www.methanetomarkets.org/documents/toolsres_coal_overview_ch3.pd*.

[3] Essentially all of South Africa's coal production is anthracitic or bituminous coal.

[4] Depending on the design of the surface mine, the use of drag lines to remove overburden and the use of bucket-wheel excavators and electric-cable shovels to extract coal will generally consume the largest share of electricity for surface mining.

[5] The average stripping ratios estimated for South African coal mines.

[6] The electrical equipment can include ventilation, electric LHD, drills, jumbos, continuous mining machines, underground crushers, conveyors, dewatering pumps, compressors, and hoists used to lift people, equipment, waste, and ore. Specific reference to 20.3kWh/t was stated for underground mines in South Africa (Eliasson and Lee, 2003).

[7] Number 6 coal. Estimates, including the total, are rounded to two significant figures.

[8] Estimate for theoretical beneficiation plant includes grinding, centrifuges, flotation, screens, and magnetic separators. A pulverizer plant for producing power plant feed is not included. The Bond work index for coal is approximately 13. Depending on the consumer, not all coal is treated beyond crushing and washing, although most is.

[9] Estimated totals are based on combining simple averages of beneficiation estimates, the range of stripping ratios, plus surface mining and rounding totals to two significant figures.

References for Table 11

BOSMIN, 2010, Overburden Slushers: Bosmin Technical Bulletin #1—Overburden slushers, last accessed December 11, 2010, at *http://www.bosmin.com/OS/os2.htm*.

Eliasson, B., and Lee, Y. (Eds.), 2003, Integrated assessment of sustainable energy systems in China, The China Technology Program—A framework for decision support in the electric sector of Shandong Province Series: Alliance for Global Sustainability Bookseries, Vol. 4, Kluwer Academic Publishers, 848 p.

Hartman, Howard, L., ed., 1992, SME mining engineering handbook (2nd ed.), vols. 1 and 2: Seeley W. Mudd Memorial Fund of AIME, Society for Mining, Metallurgy, and Exploration, 2,394 p., last accessed December 12, 2010, at *http://books.google.com/books?id=DsSmPKEOWDcC&pg=PA2061&lpg=PA2061&dq=electricity+kwh+underground+coal+mining&source=bl&ots=2NA1v2dJPg&sig=_Dw40HqBL2Qeei6YKeS49VGfcP4&hl=en&ei=hcCsTIqeAYS8lQeg5_yxCA&sa=X&oi=book_result&ct=result&resnum=2&ved=0CBsQ6AEwAAEw#v=onepage&q=electricity%20kwh%20underground%20coal%20mining&f=false*.

Metals Place, 2009, Market tendency on imports of ferroalloys: last accessed August 12, 2010, at *http://metalsplace.com/news/articles/31732/market-tendency-on-imports-of-ferro-alloys/*.

Methane to Markets, 2010, Coal mine methane global overview—Botswana: last accessed December 11, 2010, at *http://www.methanetomarkets.org/documents/toolsres_coal_overview_ch3.pdf.*

Methane to Markets, 2010, Coal mine methane global overview—South Africa, accessed December 12, 2010, at *http://www.methanetomarkets.org/documents/toolsres_coal_overview_ch27.pdf.*

Richard, D., Molburg, John, Brockmeier, Norman, and Thimmapuram, Prakash, 2000, Coal IGCC for hydrogen production, CO2 recovery, and electricity: Review for the Aspen Global Change Institute, July, 23rd, 2000, last accessed May 6, 2011, at *http://www.agci.org/dB/PPTs/00S1_RDoctor_0723.pdf.*

Singh, R.D., 2004, Principle and practices of modern coal mining: New Dehli, India, New Age International Limited, 720 p.

U.S. Department of Energy, 2010, DOE Energy and Environmental Profile of the U.S. Mining Industry—Coal: last accessed December 12, 2010, at *http://www1.eere.energy.gov/industry/mining/analysis.html*.

U.S. Department of Energy, 2010, Industrial Technologies Program, 2007: Mining industry energy bandwidth study, last accessed December 12, 2010, at *http://www1.eere.energy.gov/industry/mining/pdfs/mining_bandwidth.pdf*.

Yatagan-Mugla, T.K., 2007, Title: Middle East Technical University, last accessed December 12, 2010, at *http://www.scribd.com/doc/25366257/TKi-Summer-Practice.*

Table 12. Estimated electricity requirements (kWh/t) for the recovery of cobalt cathode from intermediate products from primary and secondary feedstock by electrowinning in chloride and sulfate media.

[kWh/t, kilowatt hours per metric ton; NA, not applicable]

Plant name and country	Media	Feedstock	Electricity requirement (kWh/t of recovered cobalt as cathode)
Jinchuan, China	Chloride	Cobalt carbonate produced from primary sources	3,400
Nihama, Japan	Chloride	Cobalt hydroxide produced from primary sources	3,100
Nikkelverk, Norway	Chloride	Cobalt carbonate produced from primary sources	3,700
Simple average of above	Chloride	NA	3,400
NA	Chloride	Secondary materials[1]	4,400[1]
Chambishi, Zambia	Sulfate	Cobalt carbonate produced from primary sources	6,500[2]
Luilu, Kinshasa	Sulfate	Cobalt hydroxide produced from primary sources	5,000-6,000[2]
Port Colborne, Canada	Sulfate	Cobalt hydroxide produced from primary sources	3,600
Shituru, Kinshasa	Sulfate	Cobalt hydroxide produced from primary sources	5,300[2]
Simple average of above	Sulfate	NA	5,300[2]
NA	Sulfate	Secondary materials[3]	3,000[3]

[1] Based on bench scale experimentation and not known to be in commercial practice. Process was designed to recover chromium chemicals and produce cobalt and nickel cathodes from super-alloy scrap.

[2] The listed plants in Kinshasa and Zambia are undergoing major renovations that have already or will likely reduce the electricity requirements per unit of cobalt cathode produced.

[3] The estimate of the electricity requirement is considered to be under optimum conditions for electrowinning cobalt in a sulfate media using secondary feedstock consisting of Alnico, super-alloy scrap, and spent catalysts.

References for Table 12

Bateman Engineering, 2001, Chambishi cobalt-purification plant: last accessed May, 2, 2011, at *http://batemanphp.syncrony.com/TECHNOLOGY/ChambishiCobaltPurificationPlant.pdf.*

Cobalt Development Institute, 2011, Trends in cobalt recovery technology: Cobalt news, no. 1, January, p. 3–6, last accessed May 2, 2011, at *http://www.thecdi.com/cdi/images/news_pdf/cobalt_news_jan2011.pdf.*

Ecomaterials Center (Japan), 2003, Estimation of CO2 emission and energy consumption in extraction of metals: National Institute for Materials Science, Independent Administrative Institution, last accessed June 7, 2011, at *http://www.nims.go.jp/imel/mde-report/Report/01-e-p.pdf.*

Peek, Edgar, Akre, Torjus, and Asselin, Edouard, 2009, Technical and business considerations of cobalt hydrometallurgy: Journal of Metals, v. 61, no. 10, p. 43–53.

Redden, L.D., and Greaves, J.N., 1992, The technical and economic aspects of producing high-purity cobalt and nickel from superalloy scrap utilizing a double membrane electrolytic cell: Hyrometallurgy, v. 29, issues 1–3, p. 547–565.

Schyff, Willem van der, 2011, An independent technical report on the material assets of Katanga Mining Limited, Katanga Province, Democratic Republic of Congo, accessed May 2, 2011, at *http://www.investis.com/katanga/technicalreport-2011/katanga-mining-limited-technical-report2.pdf.*

Sharma, I.G., Alex, Pamela, Bidaye, A.C., and Suri, A.K., 2005, Electrowinning of cobalt from sulphate solutions: Hydrometallurgy, v. 80, no. 1–2, p. 132–138.

Table 13. Generalized electricity requirements for mining and heap leaching copper oxide ores.

[kWh/t, kilowatt hours per metric ton; t, metric ton]

Process	Feedstock	Electricity requirement (kWh/t processed ore)	Electricity requirement (kWh/t copper)
	Mining		
Open pit[1]	Copper oxide ore	<1–6	600–2,500
	Processing		
Secondary crushing, stacking ore with belts or trucks, pumping solvent, solvent extraction, and electrowinning[2]	Copper oxide ore	6–21	2,200–4,500
Total mining and generalized processing technology FOB	**--**	**7–7**	**2,800–7,000**
Chile (average 2004–2008)	Copper oxide ore		
Open pit mining, t Cu	do		173
Underground mining, t Cu	do		461
Beneficiation, t Cu	do		2,100
Smelting, t Cu	Copper concentrate		1,050
Electro-refined, t Cu	Copper anode		349–600
LX-SX-EW, t Cu	Leach solutions		2,880
Services,[3] t Cu	N/A		144

[1] Electricity requirements for mining of ore expressed as per t of copper cathode can vary significantly from site to site based on factors such as stripping ratios, types of mining, and equipment used (such as electric shovels versus diesel-powered loaders), use of in-pit crushers, blasting methods, and conveyor belts or trucks to move ore to the mill. Depending on the type of mining equipment, the waste to ore ratio also affects the amount of electricity consumed. Ore grade and copper recovery significantly affect consumption of electricity when expressed as kWh/t cathode. As an example, if 17 Mt (million metric tons) of ore is mined annually at 3kWh/t and 42,000 t of copper cathode is produced annually from that ore, approximately 1,244 kWh of electricity per t of cathode is required for mining. Mines operating with an in-pit crusher and conveyor belt (as opposed to trucks) expend roughly 1,000 kWh/t copper cathode.

Accounting procedures can also affect estimates as a result of the methods used for distributing cost and consumption centers.

[2] Electricity requirements at a facility can vary between sites because of numerous factors, including ore grade, mine and metallurgical recoveries, dewatering requirements, operating days per year, and the presence or absence of an acid plant. For example, in some cold weather climates the plant may operate at 230 days per year. Copper anodes (fig. 5) produced in a smelter are sent to the refinery for electrorefining into copper cathodes (see fig. 6). Copper recovered from solution extracted through heap leaching is also processed in a refinery for electrowinning and can contain roughly 30–40 grams of copper per liter of solution. The power requirement for electrorefining copper from copper anode is approximately 661 kWh/t of copper recovered and approximately 3,000 kWh/t of copper recovered from a copper-laden acid leach solution using leaching, solvent extraction, and electrowinning (LX-SX-EW).

[3] Generally, electricity requirements for offices and infrastructure requirements, such as lighting, sanitation, and water supply.

References for Table 13

Chilean Copper Commission, 2009, Energy consumption and greenhouse gas emissions in the copper industry: last accessed September 1, 2010, at *http://www.cochilco.cl/english/productos/doc/energy_consumption_and_greenhouse.pdf*.

Davis, Michael, Sole, Kathryn, MacKenzie, Murdoch, and Virnig, Michael, 1998, Recovery of Cu and Cn by SX from solutions produced in leaching of Cu/Au ores: last accessed February, 1, 2011, at *http://www.cognis.com/NR/rdonlyres/EE1A28C0-B002-47FD-A436-C8FA9D272561/0/randolsx.pdf.*

Gustavson Associates, 2010, Pre-feasibility study update for the Contact Copper Project, Elko County, Nevada, USA: National instrument 43-101, Technical report, last accessed December 12, 2010, at *http://www.enexco.ca/_resources/Contact%20Pre-feas%20%202010.pdf.*

Henricksen, T., Mello, R., and Segsworth, W., 2009, Technical report on the Franke and Pelusa Integrated Project, Altamira District, Region II, Chile: National instrument 43-101, Technical report, last accessed December 12, 2010, at *http://www.quadrafnx.com/i/pdf/2009-02-19_Franke_NI43-101.pdf.*

Ivanhoe Copper Company Limited, S&K Operations, 2006, Responsible mining—Sustainable growth, Myanmar: Sabetaung-Kyisintaung Mine, Myanmar, last accessed December 12, 2010, at *http://www.ivanhoe-mines.com/i/pdf/SHE2007.pdf.*

Marsden, John, 2008, Energy efficiency and copper hydrometallurgy: last accessed December 6, 2010, at *http://metallurgium.com/pdf/JOM%20Energy%20Hydromet%202008%20rev5.pdf.*

Mine-Engineeer.Com, 2010, Copper mining info: last accessed February 1, 2011, at *http://www.mine-engineer.com/mining/copperm.htm.*

Mineral Escondida Limitada, 2009, Sustainable development commitment 2008, Escondida year in review, 2008, accessed December 6, 2010, at *http://www.bhpbilliton.com/bbContentRepository/docs/escondidaYearInReview2008English.pdf.*

Moskalyk, R.R., and Alfantzi, A.M., 2003, Review of copper pyrometallurgical practices—Today and tomorrow: Minerals Engineering, v. 16, no. 10, p. 893–919.

Swendseid, Tim, and Welhener, Herb, 2008, Cobre del Mayo S.A. de C.V.: Technical Report for the Piedras Verdes Copper Project, Alamos, Sonora, Mexico, last accessed December 6, 2010, at *http://www.fronteracopper.com/i/pdf/FCC_March_2008_TR.pdf.*

Western Copper Corporation, 2006, Carmacks copper property: Yukon mineral report update, last accessed December 6, 2010, at *http://miningyukon.com/Documents/Why%20Yukon/Mineral%20Property%20Profiles/CarmCarm%20Copper%20Property.pdf.*

Western States Engineering, 2007, Capital and operating cost estimate for the Emerald Isle Copper Mine, heap leach, and electro-winning plant: last accessed December 6, 2010, at *www.sierraresgroup.com/diligence/Emerald%20Isle/scope-study.doc.*

Table 14. Estimated electricity requirements for mining, beneficiation, smelting, and refining for copper oxide ores and sulfide ores.

[kWh/t, kilowatt hours per metric ton; t, metric ton; LX-SX-EW = Heap leaching, solvent extraction, and electrowinning]

Country/Product, units	Estimated electricity consumption (kWh/t ore)	Estimated electricity consumption kWh/t Cu
Australia		
Electro-refining (Townsville)		420
Botswana		
Mining and beneficiation		1,400[1]
BCL flash smelter/33 percent Cu and 38 percent Ni in matte		880[1]
Chile (average for the years 2004–2008)		
Open pit mining, t Cu		170
Underground mining, t Cu		460
Beneficiation, t Cu		2,100
Smelting, t Cu		1,000
Electro-refining, t Cu		350
LX-SX-EW, t Cu		2,880
Services,[2] t Cu		144
Democratic Republic of the Congo (Kinshasa)		
Kamoto underground (combined methods)	60	--
Kamoto concentrator	90	4,500[3]
Luilu plant	120	6,000
Smelter-Converter Technologies/product[4,5]		
INCO flash smelter/45 percent Cu in anode.		560
Mitsubishi process/55-70 percent Cu in anode.		1,200
Noranda process/65-75 percent Cu in anode.		780
Outokumpu flash smelter/55-65 percent Cu in anode.		390
Reverberatory smelter/40-45 percent Cu in anode.		850
Teniente converter/70-75 percent Cu in anode.		1,000
Electrorefining of anodes		300–350
General Estimates		
Concentrate (mining through beneficiation)		--[6]
Flash smelting		650
Electro-refining		140–660
Electrowinning		2,000[7]

[1] The estimate for mining, beneficiation, and smelting is burdened on copper. The BCL smelter produces matte and ground material that contains copper, nickel, cobalt, and precious metals. Material is exported for refining. Burdened on nickel the electricity requirement for smelting is 770 kWh/t. The electricity requirement to produce a t of matte was estimated at 290 kWh/t.

[2] Services include electricity consumed for administrative offices, general maintenance, security, and other general support operations.

[3] Includes crushing, grinding, and flotation of oxide, sulfide, and carbonate ores at the reactivated Kamoto operation. The Luilu plant roasts, leaches, precipitates, and electrowins copper and cobalt. KWh estimates are burdened on copper. Cobalt is refined separately and reported in the cobalt table.

[3] Flash smelting of copper or copper-nickel concentrate is primarily a pyrometallurgical process using oxygen and relatively minor amounts of electricity, unless an electric furnace is employed. Most of the electricity in the smelter is consumed by motors used for handling feedstock and products.

[4] The electrorefining of copper or copper from copper-nickel anodes in the most efficient operations requires approximately 0.2–0.4 kWh per kilogram of copper metal recovered from anode. An average of 0.3 kWh was used

for estimates for operations in this category type when actual data were not available. Higher estimates were used when actual data were unavailable and operations were not considered to be of optimum efficiency.

Approximately 2.5 kWh is required to recover one kg of copper by electrowinning of copper-laden leach solutions in efficiently operated facilities.

The specific electricity consumption estimates are based on selected copper operations located in various countries.

For some operations, copper is usually associated with other recoverable commodities. For example, nickel, cobalt, platinum-group metals, and other products are being produced as co- or byproducts in Botswana, Canada, and South Africa. The copper-based estimates apply only to the copper produced, so some facilities could have greater electricity consumption assignable to the nickel and cobalt output post-smelting if a single smelter matte is produced. The example for Chile includes electrorefining and SX-EW. The recovery of nickel from anode requires approximately 6,000–8,000 kWh per t of cathode nickel.

[5] Includes materials handling, which comprises from 20 to 50 percent of the total value.

[6] Ore hardness, brittleness, and size reduction of ore to optimize recoveries are major determinants in the amount of electricity required during the grinding stage. Over 90 percent of the required external energy is in the form of electricity. Estimating the amount of energy necessary to beneficiate ore, especially in the grinding stage, is very sensitive to ore grade when expressed as kWh per unit of recovered copper cathode. For example, if 20 kWh are required to crush and grind a t of ore grading 0.5 percent, the amount of electricity required to recover one t of copper is about 4,500 kWh, based on an overall copper recovery of 88 percent. However, if the ore grade is 1 percent copper and all other factors remain the same, one-half the amount of energy is required per t of copper recovered.

The presence of co- or byproduct minerals associated with ore must be considered when expressing kWh/t against a single commodity.

[7] Considered a minimum energy requirement per t of copper recovered from electrowinning.

References for Table 14

Akada, Akihiko, 2004, Effective energy utilization on Japanese copper smelters: last accessed April 21, 2011 at *http://www.prien.cl/seminarios/taller_apec/archivos/presentations/day1/02_japan_mr_akada.pdf.*

Alvarado, Sergio, Maldonado, Pedro, and Jaques, Iván, 1999, Energy and environmental implications of copper production: Science Direct, last accessed September 1, 2010, at *http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V2S-3W37P8P-4&_user=696292&_coverDate=04%2F30%2F1999&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1642972666&_rerunOrigin=google&_acct=C000038819&_version=1&_urlVersion=0&_userid=696292&md5=cedd3948c41b8ec0971a4d5cd01e91cd&searchtype=a.*

Chilean Copper Commission, 2009, Energy consumption and greenhouse gas emissions in the copper industry: last accessed September 1, 2010, at *http://www.cochilco.cl/english/productos/doc/energy_consumption_and_greenhouse.pdf.*

Cyril, Matshameko, Thuso, 2001, Preliminary investigation of energy conservation potential in the copper-nickel mining industry in Botswana: Glasgow, Scotland, University of Strathclyde MSc thesis, submitted 2001, 61 p., last accessed August 30, 2010, the University of Strathclyde web site *http://www.esru.strath.ac.uk/Documents/MSc_2001/thuso_matshameko.pdf.*

Davenport, W.G., and Partelpoeg, E.H., 1987, Flash smelting—Analyses, control and optimization: New York, Pergamum Press, 324 p.

Edelstein, D.L., 2010, Copper [advance release]: U.S. Geological Survey, Minerals Yearbook 2008, v. I, p. 20.1–20.29*,* last accessed August 25, 2010, at *http://minerals.er.usgs.gov/minerals/pubs/commodity/copper/myb1-2008-coppe.pdf.*

Hartman, Howard, L., 1992, SME mining engineering handbook (2nd ed.), v. 2: Littleton, CO, Society for Mining, Metallurgy, and Exploration, Inc.

Kamoto Copper Company, 2006, Executive summary report for Kamoto redevelopment project: last accessed April 4, 2011, at *http://www.katangamining.com/kat/operations/reportsoperational/reop2006/feasibilitystudy/060519-feasibility-study.pdf.*

Katanga Mining Ltd., 2010, Metallurgical plant: last accessed September 2, 2010, at *http://www.katangamining.com/kat/operations/keyassets/luilumetalplant.*

Lowrie, Raymond (ed.), 2002, Mining reference handbook: Littleton, CO, Society for Mining, Metallurgy, and Exploration Inc., 464 p.

Mbendi, 2004, Nickel and cobalt mining in Botswana: Investor report, last accessed September 1, 2010, at *http://www.mbendi.com/indy /ming/nkcb/af/bo/p0005.htm*, p. 1.

Moskalyk, R.R., and Alfantzi, A.M., 2003, Review of copper pyrometallurgical practices—today and tomorrow: Minerals Engineering, v. 16, no. 10, p. 893–919.

Peek, Edgar, Åkre, Torjus, and Asselin, Edouard, 2009, Technical and business considerations of cobalt hydrometallurgy: Journal of Metals, v. 61, n. 10, p. 43–53.

Pimentel, Sara, [2004], Energy consumption of the Chilean copper mining sector 1992–2000: last accessed April 21, 2011, at *http://www.prien.cl/seminarios/taller_apec/archivos/papers/04_paper_cochilco_sara_pimentel.pdf.*

Pitt, C. H., and Wadsworth, M. E., 1980, An assessment of energy requirements in proven and new copper processes—Final report: United States Department of Energy, Division of Industrial Energy Conservation, Contract no. EM-78-S-06-07-1743, 379 p., last accessed on April 21, 2011, at *http://www.osti.gov/energycitations/purl.cover.jsp;jsessionid=18EE9BD9C71275F95814073225497B2A?purl=/6878932-ffJrQ8/.*

Rajput, R.K., 2006, Utilisation of electrical power: New Delhi, India, Laxmi Publication Ltd., 709 p., last accessed February 3, 2011, at *http://books.google.com/books?id=6z0wRsbPxI4C&pg=PA152&lpg=PA152&dq=kwh+nicken+refining&source=bl&ots=UazObM9a7x&sig=UtMqEY42S2nw6DiXIU21NOsbaxM&hl=ee&ei=Fg1KTeLLJ4j4swPRotjhCg&sa=X&oi=book_result&ct=result&resnum=1&sqi=2&vev=0CBMQ6AEwAA#v=onepage&q=kwh%20nickel%20refining&f=false.*

Riekkola-Vanhanen, Marja, 1999*,* Finnish expert report on best available techniques in copper production and by-production of precious metals: Finnish Environmental Institute, last accessed June 14, 2011, at *http://www.ymparisto.fi/download.asp?contentid=10736&lan=en.*

Rio Tinto-Kennecott Utah Copper, 2010, Company website: last accessed September 22, 2010, at *http://www.kennecott.com/our-company/facts-about-our-operation/08-08-22.*

Rosenqvist, Terkel, 2004, Principles of extractive metallurgy (2nd ed.): Trondheim, Norway, Tapir Academic Press, 506 p.

Warczok, Andrej, and Riveros, Gabriel, 2004, Energy efficiency in batch, continuous and one-step copper pyrometallurgical processes: last accessed April 21, 2011 at *http://www.prien.cl/seminarios/taller_apec/archivos/presentations/day2/08_unicersidad_de_chile_profs_warczok_and_riveros.pdf.*

Xstrata, 2009, Xstrata Copper North Queensland sustainability report 2009: last accessed September 1, 2010, at Xstrata Web site *http://www.xstrata.com/assets/pdf/xcu_sustainability_2009_northqueensland.en.pdf.*

Figure 5. Copper anode arrives at a refinery for electrorefining (electrolysis). Each anode weighs approximately 320 kg and is approximately 99.6 percent copper (Kennecott Utah Copper, 2011). Photograph provided courtesy of Rio Tinto's Kennecott Utah Copper.

Figure 6. Photograph of electrolytic cells in a copper refinery. Racks of anodes are lowered into an acid solution interleaved with stainless-steel cathode starter sheets. For 10 days, an electric current is sent between the anode and the cathode, causing the copper ions to migrate from the anode to the cathode by electrolysis. Impurities, including gold and silver, fall to the bottom of the tank holding the solution and are collected for further processing. The electrolytic process results in the formation of a cathode that contains 99.99 percent copper. Each cathode weighs approximately 130 kg (Kennecott Utah Copper, 2011). Note technician (white arrow) for scale. Photograph provided courtesy of Rio Tinto's Kennecott Utah Copper.

Table 15. Generalized electricity requirements for mining and processing diamondiferous kimberlitic and lamprolitic pipes (weathered and fresh) from selected open pit mines.

[kWh/t, kilowatt hours per metric ton][1]

Process	Feedstock	Electricity requirement (kWh/t processed ore)
	Mining	
Open pit[2]	Weathered and fresh ore	<1
	Generalized processing technology	
Crush, grind, heavy-media separation, X-ray optical sorter, grease tables, and acid cleaning[3]	Weathered and fresh ore	15–20
Total mining and processing FOB site		**16–21**

[1] Estimates are based on surface operations at the Argyle mine, Australia; the A6 and the Boteti prospects; the Damtshaa, Jwaneng, Letlhakane and Orapa mines in Botswana; and DeBeers' worldwide operations. The Diavik mine, located in the Northwest Territories, Canada, was evaluated but not included in the averages owing to the high electricity requirements resulting from its geographical location (high latitude and surrounded by dikes holding back lake water that require high-capacity pumps for dewatering). The averages of the facility's operational data pertaining to consumption of electricity for the years 2007 through 2009 were approximately 150 kWh/t of ore and 45 kWh/recovered carat. Underground mining at Diavik is suspended and is not included in the estimates. Estimates are highly dependent on factors such as diamond abundance per unit of ore, recoverability, size, and technology applied. Generally, deposits containing gem quality diamonds are lower in abundance, resulting in a significantly higher per carat electricity consumption. Deposits with a high carat count per unit of ore nearly always are mined for smaller and flawed industrial-quality stones.

[2] Little electricity is used in pits, except in some cases for belts, lighting, pumping, and so forth. Almost all mining equipment (shovels and trucks) and in-pit supporting activities operate using diesel fuel. If electric shovels and in-pit belts are used, electricity requirements could reach 1 kWh/t.

[3] The application of the principle of diamond recovery related to the mineral's specific gravity as described is generalized, but it is in widespread use throughout the "hardrock" diamond mining industry. Primary and secondary crushing and grinding technologies, degree of size reduction, and methods for separation of "heavies" vary between sites. Estimates for sites evaluated, with the exception of Diavik, vary from approximately 12–45 kWh/t of ore treated. The higher estimates are for recently investigated prospects that in general contain fewer carats per t of ore.

References for Table 15

Debswana, 2007, Annual review 2006: last accessed August 9, 2010, at *http://www.debswana.com/About%20Debswana/reports1/Debswana%20AR%202006.pdf.*

Debswana, 2009, Annual review 2009: last accessed August 9, 2010, at *www.debswana.com.*

Diavik, 2010, Rio Tinto-Diavik Diamond Mine: Diavik, media releases, last accessed August 9, 2010, at *http://www.diavik.ca/ENG/media/1131_media_releases.asp?START=20&searchKeyword1=&searchKeyword2=&searchKeyword3=&searchKeyword4.*

MSA Geoservices (Pty) Ltd, 2010, AK6 Kimberlite Project: Technical report NI 43-101 for the AK6 Kimberlite Project, Botswana, last accessed August 9, 2010, at *http://www.lucaradiamond.com/i/pdf/AK6_Technical_Report.pdf.*

MSA Group, 2010, Boteti Kimberlite Project: Technical report NI 43-101 on the Boteti Kimberlite Project, Botswana, last accessed August 9, 2010, at *http://www.lucaradiamond.com/i/pdf/Boteti_Technical_Report.pdf.*

Rio Tinto, 2010, Argyle Diamond Mine: last accessed August 9, 2010, at *http://www.argylediamonds.com.au/.*

Table 16. Generalized electricity requirements for recovering diamonds from alluvial and colluvial deposits.

[kWh/t, kilowatt hours per metric ton; FOB, free on board][1]

Process	Feedstock	Electricity requirement (kWh/t processed ore)
	Mining	
Surface[2]	Alluvial and/or colluvial material	<0.25–1.0
	Processing	
Scrubbing, jigging, heavy (dense)-media separation, X-ray optical sorting, grease plant, and acid cleaning[3]	Alluvial and/or colluvial material	6–10
Total mining and processing FOB site[3]	**N/A**	**6–11**

[1] Estimates do not apply to offshore mining of marine diamonds.

[2] Little electricity is used in "dry" mining operations. Diesel-fueled front-end-loaders, shovels, rippers, and trucks comprise the majority of equipment. Electricity is used for pumps, lights, conveyor belts, and other miscellaneous equipment. Dredges and associated equipment in "wet" environments may use up to 1 kWh/t. Electricity is usually provided by on-site, diesel-fueled generators.

[3] The kWh estimates for diamond recovery are based on the technologies focused on using diamonds' high specific gravity and other "unique" characteristics for separation. They are generalized, but are in widespread use in part or in whole throughout the alluvial and colluvial diamond mining industry. A grizzly and scrubber will generally suffice for size reduction and cleaning. Crushing is usually not required. The degree of size reduction and methods for separation of "heavies" vary between sites because of factors such as diamond shape, carat content per unit treated, size, and size distribution of diamonds. The physical characteristics of the material hosting the diamonds also contribute significantly to equipment selection.

References for Table 16

Appropriate Process Technologies (APT), 2010, RG scrubbing plants—Alluvial mineral processing: Processtech, last accessed August 9, 2010, at *http://www.processtech.co.za/MediaLib/Downloads/Home/Products/INFO%20on%20RG%20SCRUBBERS%20(March%202010).pdf.*

Flow Sort, 2006, New flow sort X-ray diamond recovery machines: last accessed August 9, 2010, at *http://www.flow.co.za/writeups/NEW_RECOVERY_MACHINE.pdf.*

Gekko Systems, 2010, A revolution in diamond pre-concentration: last accessed August 17, 2010, at *http://www.gekkos.com/documents/DiamondIPJBrochurewithinserts.pdf.*

Grig, Nigel, 2010, The pre-concentration of diamonds using the InLine Pressure Jig: last accessed August 17, 2010, at *http://www.gekkos.com/documents/030ThePreConcentrationOfDiamondsUsingTheInLinePressureJig.pdf.*

Rockwell Diamonds Inc., 2009, Technical report on the Niewejaarskaal Alluvial Diamond Project, Hay District, The Republic of South Africa, For Rockwell Diamonds: last accessed August 17, 2010, at *http://www.rockwelldiamonds.com/rcw/Niewejaarskraal.asp.*

Rockwell Diamonds Inc., 2009, Technical report on the Saxendrift Alluvial Diamond Project, Hay District, the Republic of South Africa, for Rockwell Diamonds: last accessed August 17, 2010, at *http://www.rockwelldiamonds.com/rcw/TransHex.asp.*

Scott Wilson RPA, 2010, Technical report on the Chapada Alluvial Diamond Project, Mato Grosso State, Brazil: Technical report NI 43-101, last accessed August 19, 2010, at *http://www.vaaldiam.com/mining/pdf/chapada-mine-technical-report.pdf.*

Table 17. Estimated electricity requirements for production of ore from a polymetallic ore body producing two base-metal concentrates.

[kWh/t, kilowatt hours per metric ton]

Process	Feedstock	Product(s)	Estimated mine and beneficiation plant electricity usage (kWh/t ore produced)[1]
Underground mining[2]	Ore	Polymetallic ore	51
Beneficiation (crush, grind, float (producing two concentrates) and tailings disposal[3]	Ore	Precious metal concentrate and concentrate containing Cu, Co, Ni, and Zn	40
Total	--	--	**91**
Crushing[3]	Ore	Crushed ore	3–7
Grinding[3]	Crushed ore	Ground ore	12–16
Flotation (two concentrates)[3]	Ground ore	Concentrate	7–14
Tailings (waste) treatment and disposal[3]	Tailings (slurry)	Tailings (slurry)	2
Other[4]	N/A	N/A	1–3
Total	--	--	**25–42**

[1] All power supplied by grid (externally generated).

[2] An 800,000 t/yr underground open-stoping operation requiring backfill (0.5 t fill: 1 t ore). Ore is accessed by spiral incline. Ore is brought to the surface using diesel trucks and loaders loaded at stopes. Paste backfill uses approximately 8 kWh/t to prepare and place in mined-out stopes. The estimate is not representative for all underground mining. The amount of electricity consumed per unit of ore can vary significantly within a mining operation and between mining operations. Major factors affecting electricity consumption include the amount of workings, depth, mining method, the types of mining equipment employed to extract ore and waste rock, and the ventilation and pumping requirements for dewatering. Polymetallic ores are also mined by surface methods.

[3] Ore is standard crush, grind, and float. Concentrates are shipped from site. Energy requirements for crushing and grinding can vary considerably based on size of material fed to the crusher, desired grinding size for optimum recoveries, mineralogy, and Bond work index. Values for flotation will vary depending on a number of factors that include the number and type of concentrates produced, types of equipment, the number of circuits, efficiency, and methods employed for filtering and drying concentrate.

[4] "Other" includes lighting, bagging, loading, possibly heating, and other equipment.

References for Table 17

Natural Resources Canada, 2005, Benchmarking the energy consumption of Canadian underground bulk mines: last accessed August 5, 2010, at *http://oee.nrcan.gc.ca/publications/industrial/mining/bulk-mine/BulkMines-1939A-Eng.pdf*.

Natural Resources Canada, 2005, Benchmarking the energy consumption of Canadian open-pit mines: last accessed August 5, 2010, at *http://oee.nrcan.gc.ca/publications/industrial/mining/open-pit/*.

Vulcan Resources Limited, 2008, Review of the Kylylahti feasibility study: Project No. 7343, last accessed August 19, 2010, at *http://otc.nfmf.no/public/news/10017.pdf*.

Table 18. Estimated electricity requirements for producing selected types of common ferroalloys.
[kWh/t, kilowatt hours per metric ton]

Product /country, site name, or company)	Electricity usage (kWh/t product)	Specifications and metallurgical recoveries[1]
	Ferromanganese	
China	580–1,800	Hot charge (low) and cold charge (high) for low-mid-carbon FeMn
China	2,600	NA
Gabon (ore is processed in Norway, United States, and other countries)	2,152	78.1 percent Mn, 12.7 percent Fe
India	2,400–2,800	70–80 percent recovery
India	2,600–3,000	85–90 percent recovery
Average for India	3,000–3,500	High carbon, 1.2 percent C
South Africa	2,600	78 percent Mn, High carbon
South Africa	3,100	80 percent Mn, Medium carbon
General world estimate	2,000–2,600	NA
	High Carbon Silicomanganese	
China	4,200	NA
India	3,765–9,869	NA
India	4,750–5,250	60–70 percent Mn, 10–20 percent Si, and 20 percent C
India (average)	4,875	NA
South Africa	3,860–4,840	NA
South Africa	4,000	65 percent Mn
Average 27MW furnace	3,500–4,000	70 percent Mn, 88 percent plant recovery
	Ferrovanadium	
South Africa	1,100	80 percent V (vanadium oxide feed for upgrade)
General	3,200	42 percent V and 53 percent Fe
	Ferrosilicon	
China	8,500–9,000	FeSi 75 percent
India	9,000–10,000	75–90 percent silicon
India	8,166	72–74 percent Si, 24–26 percent Fe. Plant recovery 88–95 percent
India	8,000	NA
General	6,000	45 percent Si
General	9,000	75 percent Si
	Ferrotitanium	
General	7,500	26 percent Ti

[1] Product specifications may vary. Specification data may be incomplete. NA, not available.

References for Table 18

Beijing Sino-Steel, 2009, New plants and ferroalloy making: last accessed May 19, 2011, at *http://www.ssit.com.cn/detail.aspx?articleid=147.*

Crous, P. C., 2008, High Grade Mn Ore—Outlook for the Kalahari Managanese Field, in IMnI Annual Conference, 2008, New Delhi, India, Proceedings: last accessed May 16, 2011, at *http://www2.manganese.org/documents/2008AC_Crous.pdf.*

Ecomen Laboratories Pvt. Ltd., 2009, Executive summary for public hearing of ferrosilicon plant (8,940 metric tonnes per annum): last accessed September 6, 2010, at *http://megspcb.gov.in/Documents/Executive%20Summary_English.pdf.*

MJC Energy, 2009, Energy audit in ferroalloy industry: last accessed September 7, 2010, at *http://www.emt-india.net/Presentations2010/06-Iron&Steel_9Mar2010/9MCJ.pdf.*

Ideas 1st Research, 2010, Manganese research: last accessed April 7, 2011, at *http://ideasfirst.in/Admin/Downloads/Reports/1580573763_Manganese%20Report%20-%20Final%20-%2031May20101.pdf.*

Indiamart, 2011, SR Group-India website: last accessed September 7, 2010, at *http://www.indiamart.com/company/1049874/products.html.*

Indian Bureau of Mines, 2008, Indian Minerals Yearbook 2008: last accessed September 6, 2010, at *http://ibm.nic.in/ferroalloys.pdf.*

John Wiley & Sons, Inc., 2004, Manganese and manganese alloys, *in* Kirk-Othmer Encyclopedia of Chemical Technology (5th ed.): John Wiley & Sons, Inc., last accessed September 19, 2010, at *http://www.scribd.com/doc/30131804/Manganese-and-Manganese-Alloys.*

Metal-Pages, 2009, Chinese ferro-alloys weekly roundup—Silicon defies general weakness: last accessed September 6, 2010, at *http://www.metal-pages.biz/news/story/37951/.*

Olsen, Sverre, Tangstad, Merete, and Lindstad, Tor, 2007, Production of manganese ferroalloys: Trondheim, Norway, Tapir Academic Press, 247 p.

Republic of South Africa Department of Minerals and Energy, 2008, Operating mines and quarries and mineral processing plants in the Republic of South Africa, Directory D1/2008, accessed August 8, 2011, at *http://www.blacklite.co.za/Portals/0/BEE_in_Mining_legislation/Mineral%20economics.pdf*

Senapati, Dhananjaya, Maheswar, Uma, and Ray, C.R., 2006, Ferrosilicon operation at IMFA— A critical analysis: last accessed September 6, 2010, at *http://www.pyrometallurgy.co.za/InfaconXI/037.pdf.*

Tangstad, M., Calvert, P., Brun, H., and Lindseth, A.G., 2004, Use of COMILOG ore in ferromanganese production: last accessed September 7, 2010, at *http://www.pyrometallurgy.co.za/InfaconX/072.pdf.*

Vermaak, Matthys, 2006, Vanadium recovery in the electroaluminothermic production of ferrovanadium: last accessed September 7, 2010, at *http://upetd.up.ac.za/thesis/submitted/etd-07242006-114924/unrestricted/00front.pdf.* Note: Except for South Africa, data contained in this source are from a 1945 reference and likely overstate electricity requirements if used as a proxy for currently applied technologies.

Table 19. Electricity requirement for the production of charge-grade ferrochrome and electrolysis of chromium metal in a solution of sulfuric acid.

[kWh/t, kilowatt hours per metric ton]

Technology	Electricity consumption, kWh/t of ferrochrome (f) or chromium (c)
China	
Electric arc furnace	2,600–3,200 (f)
Plasma arc electric furnace	4,600 (f)
Finland	
Outokumpu process	3,500 (f)[1]
India	
Electric arc furnace	3,100–4,000 (f)[2]
South Africa	
Outokumpu process	3,200 (f)[1]
Premus process	2,400–2,700 (f)[1]
Zimbabwe	
Electric arc furnace	4,000 (f)[1]
World (estimated range)	**3,200–5,000 (f)[1]**
General estimate	
Electrolysis	18,500 (c)[3]

[1]Includes (1) ore processing (primarily of lumpy ore); (2) blending silica and coke fines with a suitable binder; (3) pelletizing; (4) sintering; (5) preheating in a shaft furnace; and (6) melting in a submerged arc electric furnace. Estimates of electricity consumption are likely under optimum conditions. Mining is not included.

There are basically two major types of ferrochrome: charge ferrochrome and high-carbon ferrochrome (HCFeCr). Charge ferrochrome has a relatively low chromium content (typically 48–58 percent), a Cr:C ratio of 6.5:1, and a Cr:Si ratio of 12:1. HCFeCr contains 58–70 percent chromium, has a Cr:C ratio of about 9:1, and a Cr:Si ratio of greater than 100:1. Iron comprises roughly 35 percent of the content in both types.

Charge ferrochrome is produced from chromite ore with relatively low chrome content, such as those mined in South Africa. The alloy is a critical component in the manufacture of stainless steel with a chromium content usually ranging from 10 to 20 percent, whereas high carbon ferrochrome produced from high grade ore found in Kazakhstan is more commonly used in specialized applications such as engineering steels. A high Cr to Fe ratio and minimum levels of other elements such as sulfur, phosphorus and titanium are important. Except for a small amount produced for special alloys, nearly all of Africa's production is in the form of charge ferrochrome, virtually all from South Africa.

State-of-the-art ferrochrome smelter facilities include blending of chrome ore with coke, coal, quartzite, and other materials that are preheated to form briquettes or pellets and fed to closed AC-based submerged-arc-furnaces of varying sizes. Estimates of the kilowatt hours (kWh) of electricity required to produce a t of charge ferrochrome assaying approximately 53 percent chromium, 35 percent iron, 6–8 percent carbon, and 1.5–4 percent silicon were developed for several major types of processing methods from published data and communications with individuals familiar with the industry. The consumption of electricity to produce a ton of charge ferrochrome was determined by numerous factors that included the type of ore smelted (fine versus lumpy ore), feedstock preparation prior to smelting (preheated or "cold;" pelletized or sintered), and the type of furnace employed (AC or DC; open or closed).

The Outokumpu process is widely used because of its relatively low energy requirements. The Boshoek plant in Rustenberg, South Africa, achieved these levels of efficiency during early performance tests (Bateman, 2002). Samancor's plants in South Africa use the Outokumpu process include the Ferrometals and Tubatse facilities. Xstrata's plants using the process include the Rustenburg and the Wonderkop, also in South Africa.

The estimates include the steps of ore-milling; blending with silica, coke fines, and a suitable binder; pelletizing; and sintering and preheating in a shaft furnace from which gravity feeds a submerged-arc-AC furnace. The closed furnace allows the capture of the CO-rich furnace gas, which is then used to fuel the pre-heating shaft furnace and the sinter furnace.

The Premus method, which is technologically similar to the Outokumpu design, is employed in Xstrata's South African Lion facility for the production of charge ferrochrome and reportedly uses less electricity (in the range of 2,400–2,700 kWh) compared to older conventional plants that require approximately 3,900 kWh per t of charge ferrochrome (McCullough and others, 2010; Naiker and Riley, 2006; Visser, 2006; Xstrata, 2010). Much of the reduced electricity requirement results from pre-reduction (sintering) of the feedstock using fossil fuels and waste gases.

Approximately 4,200 kWh are required when an AC furnace is directly charged with a blend of "cold" lumpy chromite, reductant, silica, and other materials. It was estimated that 5,000 kWh per t of ferrochrome is required when a "cold" blend of fine chromite ore, reductant, silica, and other materials are fed to the smelter, but this process is being phased out as energy costs and energy availability are a focus of concern in the industry (Xstrata Alloys-Merafe, 2006). The direct smelting of ore in DC arc furnaces uses approximately 4,800 kWh of energy to produce a t of ferrochrome, but preheating and sintering the ore can reduce the electrical requirements to approximately 3,600 kWh/t (McCullough and others, 2010; Xstrata Alloys-Merafe, 2006).

Zimbabwe's Maranatha Ferrochrome Ltd., Zimasco, and Zimbabwe Alloy Ltd. operations produce HCFeCr and LCFeCr containing from 55 to 65 percent chromium (John Papp, mineral commodity specialist, oral commun., August 12, 2010; Shoko and Chirasa, 2004). Considering the state of the facilities and older technologies employed, about 4,000 kWh of electricity might be a reasonable assumption to produce a ton of ferrochrome. Energy requirements would likely decrease if capital intensive improvements are completed by Chinese companies.

[2] Lower value represents production of charge ferrochrome with preheated feedstock. The higher end of the range represents production of charge ferrochrome using briquetted feed without preheating.

[3] The estimated electricity requirement to recover chromium metal by electrolysis. Process follows the use of the electric furnace and the removal of iron from a chromium sulfate solution.

References for Table 19

Bateman, 2002, South African ferrochrome exceeds criteria in performance test: Globe 39, last accessed September 6, 2010, at *http://www.bateman.co.za/globe39/SAFerrochrome_exceeds_criteria_in_performance_tests.htm* and *http://www.bateman.co.za/globe39/Globe%2039%20pdfs/Globe%2039%20p3.pdf.*

Beijing Sino-Steel, 2009, New plants and ferroalloy making: last accessed May 19, 2011, at *http://www.ssit.com.cn/detail.aspx?articleid=147.*

Ruffini, Antonio, 2006, South African ferrochrome production rebounds: BNET- CBS Interactive Business Network, last accessed September 6, 2010, at *http://findarticles.com/p/articles/mi_qa5382/is_200603/ai_n21388231/.*

Cartman, Robert, 2006, An analysis of ferrochrome input costs: last accessed March, 3, 2011, at *http://www.hatch.ca/mining_metals/Iron_Steel/Articles/documents/analysis_ferrochrome_inpui_costs.pdf.*

Chrome world, 2007, Outlook for ferro-chrome and other parts of the world on Cr/SS: last accessed June 7, 2011, at *http://chromeworld.blogspot.com/2007/03/outlook-for-ferro-chrome-market-by.html.*

Daavittila, J., Honkaniemi, M., and Jokinen, P., 2004, The transformation of ferrochromium smelting technologies during the last decades: Journal of The South African Institute of Mining and Metallurgy, October, 2004, last accessed September 6, 2010, at *http://www.saimm.co.za/Journal/v104n09p541.pdf.*

Ecomaterials Center (Japan), 2003, Estimation of CO_2 emission and energy consumption in extraction of metals: National Institute for Materials Science, Independent Administrative Institution, last accessed June 7, 2011, at *http://www.nims.go.jp/imel/mde-report/Report/01-e-p.pdf.*

Euroinvestor.co.uk, 2010, Outokumpu to double ferrochrome production capacity: last accessed September 16, 2010, at *http://www.euroinvestor.co.uk/news/story.aspx?id=11114059.*

Eurasian Natural Resource Corporation, 2008, An introduction to ferrochrome: Presentation to stockholders at Edinburgh, Scotland, United Kingdom, accessed August 8, 2011, at *http://www.enrc.com/PageFiles/1748/ENRC%20-%20Ferrochrome%20presentation%208%20May%20FINAL%20PRINT%20V3.pdf*

Ministry of Science and Industrial Research, 2011, Executive summary: Ministry of Science and Technology, Government of India, last accessed June 9, 2011, at *http://www.dsir.gov.in/reports/techreps/tsr079.pdf.*

Hamilton Minerals and Metals Ltd., 2009, Ferrochrome from China: last accessed September 16, 2010, at *http://www.minerals-and-metals.com/ferroalloys-ferro-alloys/ferrochrome-ferro-chrome.html.*

Ideas 1st Information Services Pvt. Ltd, 2010, Ferrochrome: last accessed March 3, 2011, at *http://ideasfirst.in/Admin/Downloads/Reports/1720868194_Chrome-Ferrochrome%20-%20Final%20-%2031Mar20101.pdf.*

Indian Metals and Ferro Alloys Limited, 2010, Annual report 2009–2010: last accessed March 2, 2011, at *http://webcache.googleusercontent.com/search?q=cache:5gRUUCu-MhcJ:www.edelweiss.in/market/annualreports.aspx%3Fco_code%3D5807%26tb%3DDR+kwh+kazakhstan+charge+ferrochrome&cd=46&hl=en&ct=clnk&gl=us&client=firefox-a&source=www.google.com.*

Jones, Andrew, 2007, The market and cost environment for bulk ferroalloys: last accessed March 3, 2011, at *http://www.pyrometallurgy.co.za/InfaconXI/081.pdf.*

Le Roux, Helene, 2006, Tata begins construction of R670m ferrochrome plant, on lookout for SA raw materials: Creamer Media's MiningWeekly.com, last accessed September 16, 2010, at *http://www.miningweekly.com/article/tata-begins-construction-of-r670m-ferrochrome-plant-on-lookout-for-sa-raw-materials-2006-08-21.*

Mëkinen, Juho, 2006, Eco-efficient solutions in the Finnish metallurgical industry: last accessed June 14, 2011, at *http://www.teollinenekologia.fi/documents/JuhoMakinen_VTT.pdf.*

McCullough, S., Hockaday, S., Johnson, C., and Barcza, N.A., 2010, Prereduction and smelting characteristics of Kazakhstan ore samples, *in* The Twelfth International Ferroalloys Congress Sustainable Future, June 6–9, 2010, Helsinki, Finland, Proceedings: Helsinki, Finland, The Twelfth International Ferroalloys Congress Sustainable Future, p. 249–262, last accessed September 16, 2010, at *http://www.pyro.co.za/Mintek/Files/2010McCullough.pdf.*

Naiker, O., and Riley, T., 2006, Xstrata alloys in profile, *in* Jones, R.T. (ed.), Southern African pyrometallurgy: Johannesburg, South African Institute of Mining and Metallurgy, 5–8 March 2006, last accessed September 16, 2010, at *http://www.pyrometallurgy.co.za/Pyro2006/Papers/297_Xstrata.pdf.*

Nandy, Bikash, Chadhury, Manoj, Kumar, Jagannath, Paul, and Bhattacharjee, D., 2009, Sintering characteristics of Indian chrome fines: last accessed March 2, 2011, at *http://findarticles.com/p/articles/mi_qa5469/is_200910/ai_n39233550/pg_2/?tag=content,col1.*

Outokumu, 2010, Ferrochrome—Background information: last accessed September 16, 2010, at *http://www.outokumpu.com/46599.epibrw.*

Outotec, 2009, Ferrochrome smelting with OPK preheating kiln, accessed September 16, 2010, at *http://www.outotec.com/37992.epibrw.*

Samancor Ltd., 2008, Our business—operations and locations: last accessed September 16, 2010, at *http://www.samancorcr.com/content.asp?subID=8.*

Samancor Ltd., 2008, Our business—products: last accessed September 18, 2010, at *http://www.samancorcr.com/content.asp?subID=9.*

Shoko, N.R., and Chirasha, J., 2004, Technological change yields beneficial process improvements for low carbon ferrochrome at Zimbabwe Alloys., *in* Tenth International Ferroalloys Congress, INFACON X—Transformation through technology, 1–4 February 2004, Cape Town, South Africa, Proceedings: Cape Town, South Africa, Tenth International Ferroalloys Congress, INFACON X—Transformation through technology, last accessed September 18, 2010, at *http://www.pyrometallurgy.co.za/InfaconX/067.pdf.*

Viser, M., 2006, An overview of the history and current operational facilities of Samancor Chrome, *in* Jones, R.T. (ed.), Southern African pyrometallurgy: Johannesburg,

South African Institute of Mining and Metallurgy, 5–8 March 2006, p. 285–296, last accessed September 18, 2010, at *http://www.pyrometallurgy.co.za/Pyro2006/Papers/285_SamancorCr.pdf.*

Xstrata, 2010, Xstrata approves R4.9 billion ferrochrome smelter expansion: Xstrasta, Company News Release, last accessed September 18, 2010, at *http://www.xstrata.com/media/news/2010/10/20/0800CET/.*

Xstrata Alloys and Merafe Resources, 2005, Welcome to Project Lion: PowerPoint presentation, last accessed September 18, 2010, at *http://www.xstrata.com/assets/pdf/xa_slides_050708_lion_Merafe.pdf.*

Xstarta, 2006, Xstrata smelter live: Mining Journal, no. 29, last accessed September 18, 2010, at *https://www.mining-journal.com/production-and-markets/xstrata-smelter-live.*

Table 20. Estimated electricity requirements for the mining and production of gold using carbon in pulp, carbon adsorption, and Merrill-Crowe processes.

[kWh/t, kilowatt hours per metric ton; GWh/t, gigawatt hours per metric ton][1]

Country, mining methods, and recovery processes	Feedstock/Product	Estimated electricity (kWh/oz gold recovered)	Estimated electricity (GWh/t gold)
Australia [open pit, carbon in leach (CIL)]	Gold ore/Refined gold	260	8.4
Burkina Faso (open pit, CIL)	Gold ore/Refined gold	800	26
Democratic Republic of the Congo (Kinshasa) [open pit, carbon in pulp (CIP)]	Gold ore/Refined gold	700	23
Ghana (open pit, CIP)	Gold ore/Refined gold	600	19
Ghana (deep underground[2], bio-ox for sulfide ore; heap leach with carbon adsorption for oxides)	Gold ore/Refined gold	2,000	64
Guinea (open pit, CIP, and heap leach with carbon absorption)	Gold ore/Refined gold	800	26
Mali (open pit, CIP)	Gold ore/Refined gold	700	23
South Africa (deep underground[2], Merrill-Crowe, CIP, and others)	Gold ore/Refined gold	2,500–3,600	80–120
South Africa (open pit, CIL)	Gold ore/Refined gold	800	26
South Africa (open pit, heap leach and carbon adsorption)	Gold ore/Refined gold	500	16
South Africa (average all mines)	Gold ore/Refined gold	2,200–2,900	71–93
Tanzania (open pit, CIP)	Gold ore/Refined gold	700	23
United States, Barrick operations (open pit, underground and processing methods that include autoclaving, gravity, roasting, heap leach, CIL)[3]	Gold ore/Refined gold	500	16
United States, Cripple Creek &Victor Gold (open pit, heap leach, and carbon adsorption)[4]	Gold ore/Refined gold	340	11
General electrorefining of gold	Gold chloride solution/Refined gold	0.009–0.0109	0.0003–0.00035

[1] Estimates of electricity requirements are based on electricity-consumption data, energy-consumption data, cash-cost data, kilowatt-hour charges, and percentage of electricity cost to cash-cost data. Numerous factors can affect energy consumption in the mines. For underground mines, major factors include extent of active and development of underground workings; number, size, and depth of shafts; ventilation and refrigeration of air; compressed air and water pumping requirements; drilling requirements; ore grade; waste and dilution; and types and amount of equipment. The underground mines in South Africa are at average depths of 2.7 km. At these depths, mines require greater amounts of energy per unit of ore for compressed air, dewatering, hoisting, and ventilating and cooling. Ambient rock temperatures in active mining areas average 55–62 degrees centigrade (C) and require a significant consumption of electricity to cool the air to about 28–32 degrees C.

Surface mines generally use trucks and loaders and therefore use less electricity per ton of ore than underground mines. Drills may be electric, but are powered by electricity generated on-site.

Electricity requirements for beneficiation and gold recovery vary. The highest energy consumption per unit of gold recovery is dependent on the work index of the ore, size of milling product, and gold recovery technologies.

All or part of the electricity consumed by ancillary facilities such as maintenance shops, administrative buildings, and housing and medical facilities are not included in the estimates, unless otherwise noted. Electricity estimates include sites and post-mine processing to gold, but do not include electricity consumed for materials and reagents purchased or consumed at offsite corporate facilities. Some operations are supplied in total by on-site generation of electricity and/or purchased in whole or in part from a grid. Not all mines and facilities drawing electricity from the grid are provided by Eskom. Estimates for countries were independently estimated, based on local factors.

[2] The "deep mines" is a term applied to a group of operations that are among the deepest in the world developed in the Witwatersrand of South Africa. These mines collectively produce more than 6 million ounces of gold annually, roughly 90 percent of South Africa's gold production. These mines require significantly more electricity per ton of ore than most other underground mines. Some of the underground mines in Ghana share some of the characteristics of the South African mines, but not to the same extent. See table 22 for specific information relating to the South African operations.

[3] Includes the Goldstrike, Marigold, and Round Mountain Mines in Nevada, United States.

[4] Data are provided for the purpose of comparison. Estimates are based on actual 2010 operational data for the Cripple Creek & Victor Gold Mine, Cripple Creek, Colorado. The major processes for recovering gold are similar to many other operations and entail: (1) crushing 20 Mt/yr ore to minus 6 inch in gyratory crusher and then minus ¾ inch in cone crushers; (2) blending with lime and other material; (3) placing ore on heap; (4) applying cyanide solutions on the heap and leaching metals; (5) carbon adsorption of metals from pregnant solution; (6) re-precipitation of gold and silver from pregnant solution onto steel wool cathode under a low electrical charge in a electrowinning cell; and (7) smelting to gold-silver doré. Barren or "stripped" cyanide solution is reconstituted and pumped to be reapplied to the heap. For 2010, the electricity requirements were estimated using actual site data at 340 kWh/oz gold recovered or 4 kWh/t ore (Jane Mannon, Manager for Community Affairs, Cripple Creek & Victor Gold Mining Company, Colorado, oral commun., October 18, 2010). Stripping ratios at the Cripple Creek & Victor Gold Mining operation are about 1:1 while the open pit mines in Ghana have stripping ratios as high as 7:1 and average about 5:1. The ore in Ghana treated by the CIL method is ground to minus 200 microns and the ore treated by heap leaching is reduced to 8–12 mm. The ore, which is also treated by the heap leaching at the Cripple Creek operation, is reduced to minus ¾ inch (19 mm) and therefore requires lesser amounts of electricity per unit of feed to the mill (see fig. 7). In general, the ores in Ghana also have a higher Bond work index than the ores in Colorado.

References for Table 20

Amiel, A., 2008, Blast fragmentation optimization at Tarkwa Gold Mine using 6 sigma methodologies: Journal of the Southern African Institute of Mining and Metallurgy, v. 108, No. 2, p. 669–681, also available online at *http://www.saimm.co.za/Journal/v108n11p669.pdf.*

AngloGold Ashanti, 2010, AngloGold Ashanti annual report for 2009: last accessed August 5, 2010, at *http://www.anglogold.com/subwebs/InformationForInvestors/Reports09/AnnualReport09/f/AGA_RR09.pdf*.

Avocet Mining, 2010, Company website: last accessed 1 August 2011 at *http://www.avocet.co.uk/inata.html.*

Banro Corporation, 2009, Release of Twangiza feasibility study: Banro, Company news release, last accessed August 5, 2010, at *http://www.banro.com/s/NewsReleases.asp?ReportID=335716.*

Barrick Gold Corporation, 2004, Goldstrike tour—September 2004: last accessed April 27, 2011, at *http://www.barrick.com/Theme/Barrick/files/docs_presentations/pr9_30_2004_wdgogo.pdf.*

Barrick Gold Corporation, 2009, Barrick earns $492 Million ($0.56 Per Share)—Cash flow rises 42 percent to $718 million: last accessed August 15, 2010, at *http://www.barrick.com/News/PressReleases/PressReleaseDetails/2009/BarrickEarns492Million056PerShareCashFlowRises42to718Million1120955/default.aspx*

Barrick Gold Corporation, 2010, The Gold Industry Leader, *in* CIBC Whistler Institutional Investor Conference, British Columbia, Canada, January 2010, Proceedings: British Columbia, Canada, CIBC Whistler Institutional Investor Conference, last accessed August 15, 2010, at *http://www.barrick.com/Theme/Barrick/files/docs_presentations/2010-CIBC-Institutional-Investor-Conference-Whistler.pdf.*

Eskom, 2010, Eskom annual report for 2009: last accessed August 15, 2010, at *http://www.eskom.co.za/annreport09/ar_2009/info_sheets/pricing_03.htm.*

Hassan, Edmund, 2007, Energy management in the extractive industry—Ghana: Tokornoo and Associates Limited, last accessed August 3, 2010, at *http://fak6.tu-freiberg.de/fileadmin/Umwelt_und_Ressourcenmanagement/expertseminar/081103_Hassan.pdf.*

Kappes, D.W., 2007, Precious metal heap leach design and practice: last accessed March 31, 2011, at *http://www.kcareno.com/pdfs/mpd_heap_leach_desn_and_practice_07apr02.pdf*

Kitco, 2010, Gold mine production—cash costs by region, Q1 10, $/oz: last accessed August 5, 2010, at *https://www.kitcomm.com/showthread.php?t=63165%20%20Gold%20mines%20production%20Costs-Kitco%20Forum.*

Marketwatch, 2008, Africa raises electricity prices by 27.5 percent: last accessed August 5, 2010, at *http://www.marketwatch.com/story/south-africa-raises-electricity-prices-by-275*.

Mular, A.L., Halbe, D.N., and Barratt, D.J. (eds.), 2002, Mineral processing plant, practice, and control proceedings, v. 2: Littleton, CO, Society of Mining, Metallurgy, and Exploration, Inc., 2,410 p.

Rajput, R.K., 2006, Utilisation of electrical power: New Delhi, India, Laxmi Publication Ltd., 709 p., portion available on-line at *http://books.google.com/books?id=6z0wRsbPxI4C&pg=PA152&lpg=PA152&dq=kwh+nicken+refining&source=bl&ots=UazObM9a7x&sig=UtMqEY42S2nw6DiXIU21NOsbaxM&hl=ee&ei=Fg1KTeLLJ4j4swPRotjhCg&sa=X&oi=book_result&ct=result&resnum=1&sqi=2&vev=0CBMQ6AEwAA#v=onepage&q=kwh%20nickel%20refining&f=false.*

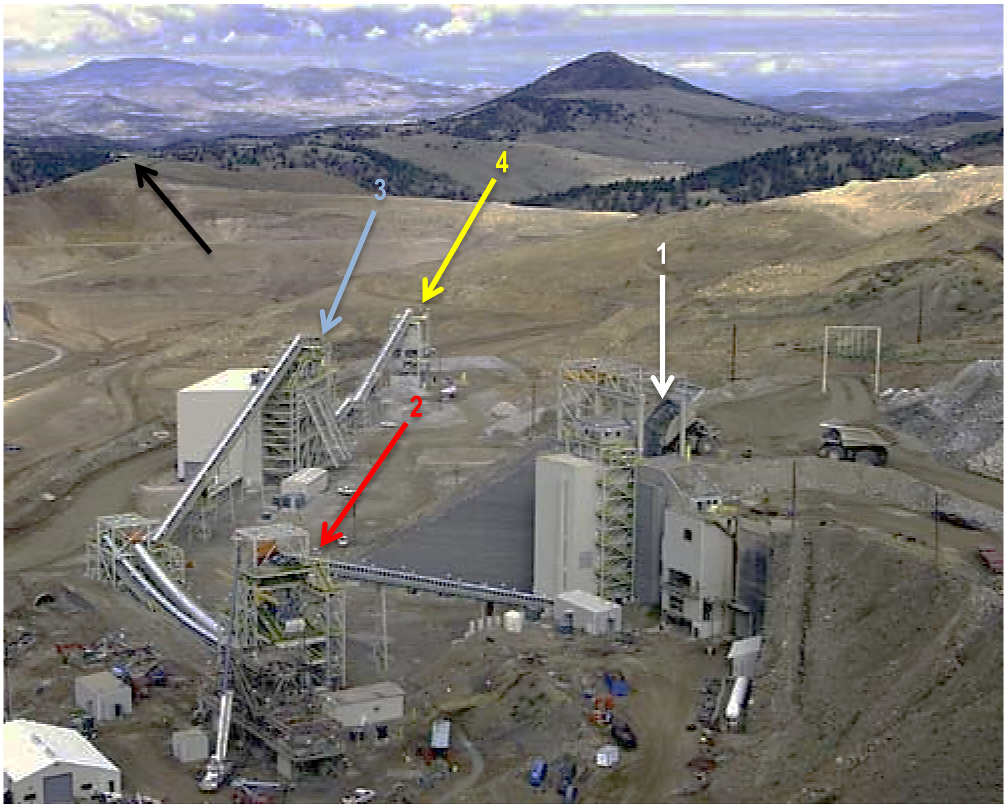

Figure 7. A photograph of the Cripple Creek & Victor Mining Company's open-pit gold operation in Cripple Creek, Colorado, showing a fairly typical heap leach gold operation: (1) gold ore being dumped into the primary crusher (white arrow); (2) ore screened for size (red arrow); (3) ore conveyed to the secondary cone crushers (blue arrow); and (4) ore being conveyed to the lime blending and load-out-bin where trucks are loaded with ore (yellow arrow). The black arrow points to a truck dumping crushed gold ore on the heap to be leached. Photograph courtesy of Cripple Creek & Victor Gold Mining Company.

Table 21. Estimated electricity requirements for the mining and production of gold from five deep-underground mines operated by AngloGold Ashanti in South Africa in 2006.

[kWh/t, kilowatt hours per metric ton][1]

Ore production/ depth/process	Great Noligwa	Kopanang	Moab Khotsong[2]	Mponeng	Tau Lekoa
Approximate tons of ore milled in 2006	2,400,000	2,000,000	70,000	1,900,000	1,500,000
Estimated mining or shaft depth (meters)	3,400	2,500	3,000	2,500	1,650
Primary mining method	Variable stoping methods	Variable stoping methods	Variable stoping methods	Grid mining	Longwall
Production (conveyors, loaders, locomotives, kWh/t ore) [3]	10	N/A	69	N/A	1[4]
Hoisting (kWh/t ore)	23	N/A	544	24	32
Ventilation (kWh/t ore)	34	32	468	39	27
Refrigeration (kWh/t ore)	6	N/A	505	N/A	Not required
Pumping (dewatering, kWh/t ore)	21	N/A	87	N/A	18
Compressed air (kWh/t ore)	7	N/A	67	N/A	12
Total estimated kWh/t ore mined[5]	**101**	**<32**	**1,740**	**<63**	**90**

[1] "Deep mines" are those developed in the Witwatersrand and collectively produce more than 6 million ounces of gold annually, roughly 90 percent of South Africa's gold production. Estimates are for ore brought to the surface. Major factors affecting electricity use include extent of active and developing underground workings; number, size, and depth of shafts; ventilation and refrigeration of air; compressed air and water pumping requirements; drilling requirements; ore grade; waste and dilution; and types and amount of equipment. The great depths of these mines require greater amounts of energy per unit of ore for compressed air, dewatering, hoisting, ventilating, cooling, and other requirements. Ambient rock temperatures average 55 degrees centigrade. Ore grades range from approximately 5.6 to 7.5 g/t.

[2] The Moab Khotsong mine was undergoing extensive development activities in 2006, resulting in disproportionate estimates for kWh/t ore when compared to active mining operations at higher levels of capacity utilization. The mine is anticipated to produce 7.67 Mt of ore in 2015, from which approximately 130 t of gold will be recovered. The higher production level will reduce the amount of electricity required when expressed against units of material recovered in several relatively fixed cost-centers, such as dewatering.

[3] Estimates include mining equipment using electricity provided by cable from the surface. Battery-driven locomotives, diesel equipment, and hydropowered (pressurized water-driven) equipment may not be included in the estimates.

[4] Mine makes heavy use of hydropower for mining, electric slushers, and battery-driven locomotives.

[5] Estimates of electricity requirements are based on electricity-consumption data, energy-consumption data, cash-cost data, kilowatt-hour charges, and percentage of electricity cost to cash-cost data. Numerous factors can affect energy consumption in the mines. For underground mines, major factors include the extent of active and developing underground workings; number, size, and depth of shafts; ventilation and refrigeration of air; compressed air and water pumping requirements; drilling requirements; ore grade; waste and dilution; and types and amount of equipment. The underground mines in South Africa are at average depths of 2.7 km. At these depths, mines require greater amounts of energy per unit of ore for compressed air, dewatering, hoisting, ventilating, and cooling. Ambient rock temperatures average 55 degrees centigrade (C).

References for Table 21

AngloGold Ashanti, 2007, UMECS-B1: AngloGold Ashanti, last accessed February 10, 2011, at *http://wiredspace.wits.ac.za/bitstream/handle/10539/7043/Appendix%20B1.pdf?sequence=1.*

AngloGold Ashanti, 2010, AngloGold Ashanti annual report 2009—Annual financial Statements: AngloGold Ashanti, last accessed February 10, 2011, at *http://www.anglogold.co.za/subwebs/informationforinvestors/reports07/AnnualReport07/review/review_za.htm.*

Handley, M.F., de Lange, J.A., Essrich, F., and Banning, J.A., 2000, A survey of the sequential grid mining method: The Journal of the South African Institute of Mining and Metallurgy, May/June 2000, last accessed February 10, 2011, at *http://www.saimm.co.za/Journal/v100n03p157.pdf.*

Lanham, Andrew, 2005, Tau-Lekoa-beating low grade with high-tonnage efficiency: Mining Weekly Online, last accessed February 10, 2011, at *http://www.miningweekly.com/print-version/tau-lekoa-beating-low-grade-with-hightonnage-efficiency-2005-02-04.*

Rebelo, Elizabeth, 2004, R4, 2bn project to increase production to 690,000 oz/y: Mining Weekly.com, last accessed February 10, 2011, at *http://www.miningweekly.com/article/r42bn-project-to-increase-production-to-690-000-ozy-2004-07-02.*

Tshisekedi, Jean Rene, 2008, Energy consumption standards and costs in South African gold and platinum mines: University of the Witwatersrand, South Africa, Masters of Science Thesis, last accessed May 6, 2011, at *http://wiredspace.wits.ac.za/handle/10539/7043.*

Table 22. Estimated electricity requirements for producing gold from four deep-underground mines in South Africa operated by Gold Fields Ltd. in 2006.

[kWh/t, kilowatt hours per metric ton][1]

Ore production/depth/process	Beatrix	Driefontein	Kloof	South Deep
Approximate tons of ore milled in 2006	3,551,000	3,867,000	3,206,000	1,256,633
Average ore grade per t of ore produced (g/t)	5.2	8.1	8.7	7.03
Estimated mining or shaft depth (meters)	705–1,962	2,307	2,665	2,031–2,550
Primary mining methods	Longwall and modified room and pillar	Longwall and modified room and pillar	Longwall and modified room and pillar	Longwall and modified room and pillar
Production (conveyors, loaders, locomotives) (kWh/t ore)	13	69	41	NA
Hoisting (kWh/t ore)	26	Included in production	59	NA
Ventilation (kWh/t ore)	29	64	141	NA
Refrigeration (kWh/t ore)	24	35	65	NA
Pumping (dewatering) (kWh/t ore)	68	133	106	NA
Compressed air (kWh/t ore)	55	99	124	NA
Gold plant (kWh/t ore)	31	64	42	NA
General services (kWh/t ore)	16	15	18	NA
Total estimated kWh/t ore mined	**262**	**479**	**596**	**438**

[1] “Deep mines” are those developed in the Witwatersrand and collectively produce more than 6 M ounces of gold annually, roughly 90 percent of South Africa’s gold production. Estimates are for ore brought to the surface. Major factors affecting the amount of electricity used in the mine include the extent of mining activities; development of additional underground workings; the number, size, and depth of shafts; requirements for ventilation and refrigeration of air; compressed air and water pumping requirements; drilling requirements; ore grade; waste and dilution; and types and amount of equipment. The great depths of these mines require greater amounts of energy per unit of ore for compressed air, dewatering, hoisting, ventilating, cooling, and other requirements. Ambient rock temperatures average 55 degrees centigrade. Electricity comprises over 98 percent of the energy used at Beatrix, Dreifontein, and Kloof.

References for Table 22

Tshisekedi, Jean Rene, 2008, Energy consumption standards and costs in South African gold and platinum mines: University of the Witwatersrand, South Africa, Masters of Science Thesis, last accessed May 6, 2011, at *http://wiredspace.wits.ac.za/handle/10539/7043.*

Table 23. Estimated electricity requirements for a small- to medium-sized gold mine using conventional underground cut-and-fill mining at 1,500 metric tons per day (tpd) using the carbon-in-pulp (CIP) leach process to recover gold.

[kWh/t, kilowatt hours per metric ton]

Product and Process	Feedstock	Product(s)	Estimated mine and beneficiation plant electricity usage (kWh/t ore produced or fed to mill)[1]
Underground mining (cut and fill)	Vein quartz and disseminated gold in schist	Gold ore	40
Crushing, grinding, CIP tank leach	Gold ore	Dore' bars	80

[1] Modeled from Apollo Gold Corporation's Black Fox project located at Timmins, Ontario. Estimates are limited to the mine through the pouring of precious metal doré bars. The waste-to-ore ratio averages approximately 0.5:1. Most of the underground equipment and movement of ore associated with this model is diesel-powered. The major consumers of electricity per unit of ore extracted by underground mining include backfilling, using waste rock and rock (mixed with cement and fly ash) for ground support, compressed air, dewatering, and ventilation. The modeled underground mine is accessed by ramps. The ore and waste are removed with trucks using ramps, as opposed to shafts presented in the previous models. The use of a shaft and electrically driven mine equipment could add 10 kWh/t of ore. The amount of electricity consumed per unit of ore can vary significantly between mining operations, even on a local basis. Estimates are limited to the consumption of electricity at the mine, mill, and onsite refinery. Energy requirements for crushing and grinding can vary considerably based on factors that include the size of material fed to the crusher, desired grinding size for optimum recoveries, mineralogy, and the Bond work index.

References for Table 23

Natural Resources Canada, 2005, Benchmarking the energy consumption of Canadian underground bulk mines: Ottawa, ON, Mining Association of Canada, 79 p., last accessed August 15, 2010, at *http://oee.nrcan.gc.ca/publications/industrial/mining/bulk-mine/BulkMines-1939A-Eng.pdf.*

SRK Consulting, 2008, NI 43-101 Technical report: Timmins, Ontario, Apollo Gold Corporation, Black Fox Project, 216 p., last accessed August 15, 2010, at *http://www.brigusgold.com/pdf/blackfox-NI_43-101.pdf.*

Table 24. Estimated electricity requirements for the production of iron ore products (lumpy and fines).
[kWh/t, kilowatt hours per metric ton]

Mine and location	Feedstock	Product	Estimated mine and beneficiation plant electricity usage (kWh/t ore produced)[1]
Sishen (Kumba) open pit, South Africa	Iron ore[2]	Lump and fine hematite	13 [3]
Khumani open pit, South Africa	Iron ore	Lump and fine	20[4]

[1] Total for lump and fine ores.

[2] The ore recovered from the Sishen pit is crushed and screened into coarse, medium, and fine sized hematite. The plant has a combined annual capacity of approximately 40 Mt of product, of which 29 Mt was produced through dense media separation and 10.4 Mt was produced by the jig plant. Approximately 82 Mt of waste rock was produced. The mine uses nine electric shovels in addition to other types of non-electric shovels. In some years prior to 2009, the haulage trucks were trolley assisted as a fuel-saving strategy. In 2009, the pantographs were discontinued to save electricity, but this resulted in increased fuel costs. The operator plans to revert to pantographs when Eskom's electricity supply problems are resolved.

[3] The estimate derived was from gigajoules consumed annually over a 4-year period, percentage of fuel-based energy, and electricity-based energy derived from grid. Includes mining operations, pantograph assisted trucks, crushing, jigging, dense media separation, stacking, and other on-site requirements. It is not known if a portion of the operation's fuel consumption is used for on-site electricity production (other than for backup generators). The stripping ratio at the mine is generally about 1.8:1 (waste to ore).

[4] The ore is considered exceptionally hard and therefore requires significant energy to reduce the size of the material to desired specifications. Mining is accomplished using wheel loaders and trucks.

References for Table 24

Chadwick, John, 2006, Sishen expansion project (SEP): International Mining Magazine, last accessed August 18, 2010, at *http://www.infomine.com/publications/docs/InternationalMining/Chadwick2006i.pdf.*

Kumba iron ore, 2008, Sustainable development report—2008: last accessed August 18, 2010, at *http://www.angloplatinum.com/pdf/2010/library/Kumba_sd%20report%202008.pdf.*

Sishen Mine, 2010, It's in the figures: last accessed August 15, 2010, at *http://www.kumba.co.za/pdf/reports/kumba_afs_09/sishen_mine.pdf.*

Table 25. Estimated post-mining electricity requirements for the production of iron and steel.
[kWh/t, kilowatt hours per metric ton]

Process	Electricity consumption (kWh/t)
Crushing and grinding iron ore	20–30
Pelletizing iron ore	20–35
Direct reduced iron from iron ore (fluid bed furnace)	110–180
Direct reduced iron from iron ore (kiln)	70–100
Direct reduced iron from iron ore (rotary hearth furnace)	90–120
Direct reduced iron from iron ore (shaft furnace)	110–130
Direct reduced iron from scrap (coal or natural gas-heated furnaces)	75
Steel from pig iron or scrap (electric furnaces) [1]	500–680

[1]Approximately 110 kWh/t of additional electricity is necessary to roll and finish steel.

References for Table 25

ArcelorMittal, 2008, The lifeblood of a developing nation: ArcelorMittal South Africa Limited, Sustainability Report 2008, last accessed August 24, 2010, at *http://www.arcelormittal.com/rls/data/upl/720-1-1-SustainabilityReport_arcelormittalSouthAfrica.pdf.*

Devaux, M., 2001, The application of industrial gases to steelmaking: All Business, last accessed August 20, 2010, at *http://www.allbusiness.com/primary-metal-manufacturing/steel-product/803461-1.html.*

Eloranta, Jack, 1997, The efficiency of blasting verses [sic] crushing and grinding: last accessed April 4, 2011, at *http://webcache.googleusercontent.com/search?q=cache:dwXrgR__r7sJ:www.elorantaassoc.com/eob97.htm+kwh+crush+grind+iron+ore&cd=2&hl=en&ct=clnk&gl=us&client=firefox-a&source=www.google.com*

European Commission, Joint Research Center, 2009, Summary on energy efficiency issues in the BREF series: A report by the European Commission, Institute for Prospective Technological Studies, Sustainable Production and Consumption Unit, last accessed August 24, 2010, at *ftp://ftp.jrc.es/pub/eippcb/doc/ene_summary_in_bref_series.pdf.*

Hot Briquetted Iron Association, 2003, DR process economics: last accessed April 4, 2011, at *http://docs.google.com/viewer?a=v&q=cache:brDuYzAOJzUJ:www.hbia.org/pdf/ShortCourse_Indy/DR%2520Short%2520Course%2520-%2520Whipp%2520PPT%2520Pt.%25204.ppt+iron+ore+kwh&hl=en&gl=us&pid=bl&srcid=ADGEESix8s-wblcQnYswy8coOWVY8cGyXgzhMPn6Qdb8OoiR8hqKYks-hA9kcc9H7jNZnstXUZdEdqUPVCDx8NkjHPwfEww-E9qXEdH5EJqv5GjmLysi55MQG4vckAYIWgfGbg4qnkGR&sig=AHIEtbSxnzNGDt3aDzvJxVII-c2kYw9UfA.*

Jones, J.A., 2010, Electric arc furnace steelmaking, *in* Steel Works: American Iron and Steel Institute, last accessed August 20, 2010, at *http://www.steel.org/AM/Template.cfm?Section=Articles3&CONTENTID=21169&TEMPLATE=/CM/HTMLDisplay.cfm.*

Metso Minerals, 2004, Grate-kiln system for iron ore pelletizing: last accessed April 4, 2011, at *http://www.metso.com/miningandconstruction/MaTobox7.nsf/DocsByID/FD649B46389D826E42256B9500317622/$File/Great_Kiln.pdf.*

Nationmaster, 2006, Electricity consumption by iron and steel industry by country in 2005: last accessed August 19, 2010, at *http://www.nationmaster.com/graph/ene_ele_con_by_iro_and_ste_ind-electricity-consumption-iron-steel-industry.*

Olatunji, K.J., Durojaiye, A.G., 2010, Determination of Bond index of Birnin-Gwari Iron Ore in Nigeria: Journal of Minerals & Materials Characterization & Engineering, v. 9, no. 7, p. 635–642, also available on-line *at http://www.imp.mtu.edu/jmmce/issue9-7/issue9-7%20P635-642.pdf.*

Research Channel Africa, 2009, South Africa's steel industry: last accessed August 23, 2010, at *http://us-cdn.creamermedia.co.za/assets/articles/attachments/24314_steel_09.pdf.*

Stack, Axel, von Muhlbauer, Alfred, and Kramer, Carl (eds.), 2005, Handbook of thermoprocessing technologies: Vulkan-Verlag Gmbh, 807 p.

Worrell, Ernst, Neelis, Maarten, Price, Lynn, Galitsky, Christina, and Nan, Zhou, 2007, World best practice energy intensity values for selected industrial sectors: Ernest Orlando Lawrence Berkeley National Laboratory report LBL-62806, last accessed on August 23, 2010, at *http://ies.lbl.gov/drupal.files/ies.lbl.gov.sandbox/62806.pdf.*

Table 26. Estimated electricity requirements for the production of lime-based products.

[kWh/t, kilowatt hours per metric ton; tpd, metric tons per day]

Process and Product	Feedstock	Estimated electricity usage (kWh/t product[1])
Pre-calcining		
Ore preparation (crushing and grinding).	Limestone and dolomitic limestone	25–40
Stand-alone calcining operation[2]		
Shaft furnace @60–200 tpd (second most common practice used in Europe)	Limestone or dolomitic limestone	5–15
Parallel flow regenerative (PFR) kiln @100–600 tpd (most common in Europe)	Limestone or dolomitic limestone	20–40
Annular shaft kiln @80–300 tpd (an obsolete technology in most countries in Europe and in the U.S.)	Limestone or dolomitic limestone	18–35 for grain size from 40 to 150mm and up to 50 kWh/t for grain sizes greater than 40 mm.
Long rotary kiln@ 160–500 tpd (method is mostly obsolete in industrialized economies)	Limestone or dolomitic limestone	18–35
Rotary kiln with preheater@100–1,500 tpd	Limestone or dolomitic limestone	17–45
Small “cottage-industry” sized shaft kiln @ 50 tpd	Limestone or dolomitic limestone	30[4]
Vertically integrated operation (ore preparation through calcining)[3]		
Rotary kiln (lime or hydrated lime, average for United States production in year 2000[5])	Limestone or dolomitic limestone	67–70
Variable kiln types and capacities	Limestone or dolomitic limestone	40–140
General vertically integrated operation producing ground lime product (including crushing, grinding, calcining in a parallel flow regenerative (PFR) lime kiln, regrinding, and dust control)	Limestone	62–129
Vertically integrated gas suspension kiln (ore prep through kiln and product) at 450.	Limestone or dolomitic limestone	33
Post-calcining		
Grinding of lime (post calcining)	Lime product	Additional 4–10 for finer material and 10–40 for coarser material.
Hydrating of lime (post calcining)	Lime product	5–30
Environmental controls		
Dust control to meet European standards	General	7–9

[1] Lime producers may generate electricity on site because of the remoteness of their location and lack of access to a grid. Estimates can be variable depending on technologies used, efficiencies of operations, and product types. Energy requirements for crushing and grinding can vary considerably based on size of material fed to the crusher, desired grinding size to meet specifications, mineralogy, and Bond work index.

[2] "Stand alone" estimates do not include ore crushing and grinding.

[3] Estimates of electricity requirements are based on crushing and grinding of dolomitic limestone, followed by calcining in kilns, crushing, grinding, hydrating, and bagging. Post-kiln treatments of the calcine are determined by application; for example, agricultural or industrial application for pollution control.

[4] Electricity requirements for a 50 tpd single shaft lime kiln. Estimate does not include crushing, grinding, or other pre- or post-kiln operations. Some cottage-industry sized lime plants may employ hand breakage of rock and use diesel generators to supply the power to produce less than several hundred tons of product (varying in quality) per year.

[5] M. Michael Miller, Lime commodity specialist, U.S. Geological Survey, oral and written commun., February 16, 2011.

References for Table 26

European Commission, 2010, Reference document on best techniques in the cement, lime, and magnesium oxide industries: last accessed August 18, 2010, at *http://eippcb.jrc.es/reference/.*

Maerz, 2002, The Maerz parallel flow regenerative lime kiln: last accessed April 5, 2011, at *http://www.maerz.com/downloads/downloads_brochures/pfr.pdf.*

Maerz, 2010, Meeting new market requirements with large Maerz PFR kilns: last acccesed August 18, 2010, at *http://www.internationallime.org/doc/LECHNER%20Stephan.pdf.*

Meier, Anton, Gremaud, Nicolas, and Steinfeld, Aldo, 2005, Economic evaluation of the industrial solar production of lime: Energy Conversion and Management, no. 47, p. 905–926, also available on-line at *http://www.pre.ethz.ch/publications/journals/full/j105.pdf.*

Practical Action, 2011, Lime production—Traditional batch techniques in Chenkumbi: Practical Action, Technical Information Online, last accessed April 5, 2011, at *http://practicalaction.org/practicalanswers/product_info.php?cPath=27_66&products_id=246.*

Table 27. (*A*) Estimated electricity requirements for the production of dead burned and fused magnesia (magnesium oxide).

[kWh/t, kilowatt hours per metric ton]

Process	Feedstock	Product	Estimated plant electricity usage (kWh/t product)[1]
Dead-burned magnesia	Magnesite	Dead-burned magnesia	75–180[2]
Electric arc furnace	High-grade magnesite or calcined magnesia	Magnesia	3,500–4,500

[1] Does not include the electricity required to mine ore or produce other materials required in production.

[2]Dead burned magnesia, a less energy intensive product than magnesia produced in electric arc furnaces, is produced in rotary or shaft kilns and relies almost exclusively on fossil fuel for generating the heat required for its production. Little operational-specific data addressing the electricity requirements for briquetting, crushing, grinding, turning kilns, and ventilation were encountered. However, considering that the process is analogous to the production of cement, the amount of electricity required to produce a ton of product is estimated at roughly 100–150 kWh/t of product.

References for Table 27*A*

European Commission, 2009, Cement, lime and magnesium oxide manufacturing industries: Directorate-General Joint Research Center, last accessed May 12, 2011, at *http://eippcb.jrc.es/reference/cl.html.*

Hughes, William, 2002, Magnesia—Forms, Applications, and Production Processes: Azom—the a to z of materials, last accessed August 19, 2011, at *http://www.azom.com/article.aspx?ArticleID=1343*

Shand, M.A., 2006, The chemistry and technology of magnesia: New Jersey, John Wiley & Sons, Inc., 266 p.

Table 27. (*B*) Magnesium metal by electrolysis and the Pidgeon process.

[kWh/t, kilowatt hours per metric ton]

Process	Feedstock	Estimated plant electricity usage (kWh/t magnesium metal)[1]
Electrolysis[2]	Primarily dolomite, magnesite, primary and byproduct brines produced from potash and fertilizer production, and seawater.	18,000–22,000
Pidgeon process (silicothermic)[3]	Primarily dolomite, magnesite, primary brines and byproduct brines produced from potash and fertilizer production, and seawater.	25,000–35,000

[1] Does not include the electricity required to mine ore or produce other materials added in the process. For example, the mining and preparation of dolomite, pumping of brines, or the approximately 1.2 kg of ferrosilicon produced in a separate plant and used as an additive that requires 13 kWh to produce 1 kg of magnesium metal in the Pidgeon process.

[2] Roughly 80 percent of total world magnesium production is carried out by the electrolytic process. Many producers use sea water or lake brines as a main source of magnesium by precipitating $Mg(OH)_2$ from sea water and either converting the $Mg(OH)_2$ to anhydrous magnesium chloride or by dissolving $Mg(OH)_2$ in concentrated hydrochloric acid to get $MgCl_2$ solution. Dried magnesium chloride is then electrolyzed by applying a molten-salt electrolysis technique.

[3] In the Pidgeon process, ground and calcined dolomite is mixed with finely ground ferrosilicon, briquetted, and charged into cylindrical nickel-chromium-steel retorts. A number of retorts are installed horizontally with either heat applied externally by electric or fossil fuels or by carbon arc furnaces. Although the Pidgeon process is more energy intensive, its chief advantage is the low capital cost, estimated at about $300–400/t of annual capacity as opposed to $10,000/t of annual capacity for an electrolysis facility. Labor costs are also lower as most of the remaining magnesium plants using the Pidgeon process are located in China. The availability of low-cost dolomite and coal to supply heat directly or indirectly to generate electricity is also advantageous in some situations.

References for Table 27*B*

Anderton, Dave, A win-win on watts: Deseret Morning News, August 7, 2005, last accessed May 10, 2011, at *http://www.deseretnews.com/article/600153637/A-win-win-on-watts.html.*

Behar, M., 1997, Global scenario of magnesium metal: National Metallurgical Laboratory-Jamshedpur, NML Technical Journal, no. 39, v. 3, p. 105–115, accessed May 9, 2011, at *http://webcache.googleusercontent.com/search?q=cache:7i9ZVxGFq2QJ:eprints.nmlindia.org/1697/+magnesium+kwh+production+ore&cd=19&hl=en&ct=clnk&gl=us&source=www.google.com.*

Chemlink Pty Ltd, 1997, Magnesium metal activities in Australia: last accessed may 10, 2011, at *http://www.chemlink.com.au/magnesium_oz.htm.*

Chemlink Australia, 1997, Magnesium oxide in Australia: last accessed May 5, 2011, at *http://www.chemlink.com.au/mag&oxide.htm.*

European Commission, 2009, Cement, lime and magnesium oxide manufacturing industries: Directorate-General Joint Research Center, last accessed May 12, 2011, at *http://eippcb.jrc.es/reference/cl.html.*

Friedrich, H.E., and Mordike, B.L., (eds.), 2006, Magnesium technology—Metallurgy, design data, applications: Germany, Springer-Verlag, 677 p.

Gao, Feng, Nie, Zuoren, Wang, Zhihong, Gong, Xianzheng, and Zuo, Tieyong, 2009, Life cycle assessment of primary magnesium production using the Pidgeon process in China: International Journal of Lifecycle Assessment, v. 14, no. 5, p. 480–489.

Halmann, M., Frei, A., and Steinfeld, A., 2008, Magnesium production by the Pidgeon Process involving dolomite calcination and MgO silicothermic reduction: Thermodynamic and environmental analyses, Industrial and Engineering Chemistry Research, v. 47. No. 2, p. 146–2,154, also available at *http://www.pre.ethz.ch/publications/journals/full/j172.pdf.*

Magnesium.com, 2004, Forum—How does Pidgeon Process Survive?: last accessed May 11, 2011, at *http://www.magnesium.com/w3/forum/read.php?thread=2221.*

Mt Grace Resources, 2002, An assessment of the greenhouse gas consequences for the proposed Batchelor Magnesium Project: last accessed May 12, 2011, at *http://www.nt.gov.au/nreta/environment/assessment/register/mtgrace/pdf/greenhousegasemissions.pdf.*

National Materials Advisory Board, 1983, Titanium—past, present, and future: Washington, D.C., National Academy Press, Publication NMAB-392, 212 p., last accessed May 11, 2011, at *http://books.nap.edu/openbook.php?record_id=1712&page=R1.*

Rajagopalan, N., Srikantan, S., Srinivasan, L.K., Kannan, G.N., and Selvakesavan, A., 2000, Developing an Energy-Efficient Electrolytic Cell for Magnesium: Journal of Minerals, Metals and Materials Society, v. 52, no. 3, p. 18–19, also available at *http://www.springerlink.com/content/b54km17m838434w5/fulltext.pdf.*

Rosenqvist, Terkel, 2004, Principles of extractive metallurgy (2nd ed.): Trondheim, Norway, Tapir Academic Press, 506 p.

SEISMIC Research, 2010, China Magnesium Corporation Ltd., Creating a vertically integrated low-cost Mg producer: last accessed May 10, 2011, at *http://www.seismicresearch.com.au/our-research/research-reports/212-china-magnesium.html.*

Simandl, G.J., Schultes, Hagen, Simandl, Jana, and Paradis, Suzanne, 2007, Magnesium—Raw materials, metal extraction, and economics—Global picture, *in* Ninth Biennial SGA Meeting, Dublin, 2007, Proceedings: Dublin, Ninth Biennial SGA Meeting, last accessed May 11, 2011 at *http://www.empr.gov.bc.ca/Mining/Geoscience/IndustrialMinerals/Documents/Magnesium.pdf.*

Thayer, R.L., and Neelameggham, R., 2001, Improving the electrolytic process for magnesium production: Journal of Minerals, Metals and Materials Society, v. 53, no. 8, p. 15–17, also available at *http://iweb.tms.org/Mg/JOM-0108-15.pdf.*

Table 28. Estimated electricity requirements for the production of manganese metal from reduced or sintered ore.

[kWh/t, kilowatt hours per metric ton]

Product and Process	Feedstock	Estimated plant electricity usage (kWh/t manganese metal)[1]
Electrolysis of aqueous solution (Nelspruit process)	Roasted manganese ore (non-electrically fired rotary kilns)	7,000–10,000
Smelting in a submerged arc furnace (unspecified location)	Roasted manganese ore	7,000 [5]

[1] Electricity requirements can vary because of quality of feedstock, operating conditions, economies of scale, and numerous other factors that affect the production process. Electricity requirements per unit of production for ancillaries associated with the facilities were not estimated, but are probably less than 15 percent of the electricity required per unit of manganese metal. The lower range of the electricity requirement estimate represents the treatment of higher grade ores, like those of South Africa**.** The only remaining manganese metal plant in sub-Saharan Africa, located in Nelspruit, South Africa, was operating as of October, 2010 and employed the electrolytic process using ore mined from mineral deposits in the Kalahari region of South Africa. The plant's annual capacity is about 27,000 t of manganese metal. The plant also produced MnO and Mn_3O_4. These require roughly the same amount of energy to produce on a per-unit of contained manganese, although some estimates for manganese dioxide, produced by electrolysis have been stated as consuming about 2,400 kWh/t of manganese dioxide. Products produced from the manganese metal at the plant also include those listed below, but amounts are unknown and likely to change as per contracted orders [click links for more information]:

- *Electrolytic manganese metal low hydrogen flake*,
- *Electrolytic manganese metal low oxygen flake*,
- *Electrolytic manganese metal stabilized powder*,
- *Electrolytic manganese metal unstabilized powder*,
- *High density manganese briquettes*,
- *Chromium aluminum briquettes*,
- *Manganese aluminum briquettes (75 percent manganese)*,
- *Manganese aluminum briquettes (85 percent manganese)*,
- *Mangano manganic oxide (Mn_3O_4)*,
- *Nitrided manganese briquettes*, and
- *Nitrided manganese flakes*.

References for Table 28

Economic Times, 2010, MOIL Ltd. Directors report: last accessed March 16, 2011, at *http://webcache.googleusercontent.com/search?q=cache:9-DanEIlLo0J:economictimes.indiatimes.com/moil-ltd/directorsreport/companyid-4501.cms+electrolytic+manganese+dioxide+production+kwh&cd=9&hl=en&ct=clnk&gl=us&client=firefox-a&source=www.google.com.*

Everett, Peter, 1983, Production of electrolytic battery active manganese oxide: last accessed March 16, 2011, at *http://www.patents.com/us-re31286.html*.

Kirk, Othmer, 2007, Manganese and Manganese Alloys, *in* Encyclopedia of chemical technology (5th ed.): Hoboken, NJ, John Wiley and Sons, available on-line at *http://www.scribd.com/doc/30131804/Manganese-and-Manganese-Alloys #open_download.*

Metals Place, 2009, Market tendency on imports of ferroalloys: last accessed August 18, 2010, at *http://metalsplace.com/news/articles/31732/market-tendency-on-imports-of-ferro-alloys/.*

Saffy, Keith, 2010, Presentation to international manganese metal industry sustainable development conference in Chongqing, 9 October 2003, *in* Manganese Metal Industry Sustainable Development Conference, Chongqing, China, October 2003, Proceedings: Chongqing, China, Manganese Metal Industry Sustainable Development Conference, last accessed August 22, 2010, at *http://www.mmc.co.za/downloads/International%20EIMn%20Sustainable%20Development%20Forum%202003%20Chongqing/06.Keith%20Saffy%20paper%20-%20english.pdf.*

Song, J., and Kang, G., 2004, A practice of ferroalloy production in an environmentally friendly and recycling way, *in* Tenth International Ferroalloys Congress, Cape Town, South Africa, 1–4 February 2004, Proceedings: Cape Town, South Africa, Tenth International Ferroalloys Congress, last accessed August 22, 2010, at *http://www.pyrometallurgy.co.za/InfaconX/002.pdf.*

United Manganese of Kalahari (Pty) Ltd., 2009, Manganese—Uses, A new mine, and the benefits of high grade ore: last accessed May 16, 2011, at *http://www.manganese.org/__data/assets/pdf_file/0003/82848/3._UMK_130909.pdf.*

Table 29. Generalized electricity requirement for the production of manganese lump and sintered ore.
[kWh/t, kilowatt hours per metric ton]

Site and mine type	Feedstock	Product	Estimated electricity usage (kWh/t product)
Groote Eylandt, Australia [1]	Manganese ore	Lump ore	80
Kalahari open pit (proposed), South Africa[2]	Manganese ore	Lump ore	16
Mamatwan open pit, South Africa [3]	Manganese ore	Sintered ore	70
Wessels underground mine, South Africa[4]	Manganese ore	Lump ore	30
Chikla underground mine, India[5]	Manganese ore	Lump ore	8–14

[1] The Groote Eylandt operation produces power on-site with diesel-powered generators to meet the needs of surface mining, ore crushing, screening, washing, and loading ore at the port using conveyor belts. The diesel-powered generators also provide power to a town site populated by approximately 1,200 individuals. The mine produces approximately 15 percent of the world's high-grade manganese ore, averaging approximately 3 million tons per year (Mt/yr).

[2] Estimate based on electricity requirements for a proposed open pit operation in the Northern Cape Province of South Africa with an average ore capacity of approximately 1.8 Mt/yr. The proposed Kalahari plant design is similar to other lump ore operations in South Africa. Operations are generally open pit using loaders (non-electric) and trucks. Ore is crushed and screened to minus 75 mm with a grade of 37 percent manganese prior to shipping. Estimates do not include roasting or sintering.

[3] Ore from Mamatwan is transported from the crusher (in-pit), crushed to 100 mm and then transported by conveyor belt approximately 2 km to a stockpile where it is further crushed. At least some ore is beneficiated using dense media. Ore is sintered in an electric furnace and moved by bucket wheel. Production is approximately 2 Mt/yr. The estimate includes crushing of ore (16 kWh/t), conveyor belt, beneficiation, sintering (30 kWh/t), and loaders. Energy requirements for crushing and grinding can vary considerably based on size of material fed to the crusher, desired grinding size for optimum recoveries, mineralogy, and Bond work index.

[4] At the Wessels mine in South Africa, ore is crushed underground, and transported to the surface by belt, screened, and shipped by train. Mine production is approximately 1 Mt/yr. Energy requirements for crushing and grinding can vary considerably based on size of material fed to the crusher, desired grinding size for optimum recoveries, mineralogy, and Bond work index. See additional discussions relating to the electricity requirements for conveyor belts in table 3.

[5] Small underground mine producing approximately 300,000 t/yr of ore consuming 8–14 kWh/t. Ore is crushed, screened, and jigged.

References for Table 29

Barloworld Equipment, 2006, The partnership just got smarter: last accessed August 22, 2010, at *http://www.bec.co.za/Media/the_partnership_just_got_smart.html.*

BHP Billiton and Manganese HSEC, 2002, Annual report 2002: last accessed April 7, 2011, at *http://www.bhpbilliton.com/bbContentRepository/Reports/ManganeseHSECRep2002.pdf.*

BHP Billiton, 2010, Mamatwan and Wessels: last accessed October 13, 2010, at *http://www.bhpbilliton.com/bb/ourBusinesses/manganese/hotazelManganeseMines/mamatwamamatwanAnd.jsp.*

Heydenrych, Amy, 2006, New type of crusher for iron-ore mine: MiningWeekly.com, last accessed October 13, 2010, at *http://webcache.googleusercontent.com/search?q=cache:i_z5msRa7uoJ:www.miningweekly.com/article/new-type-of-crusher-for-ironore-mine-2006-08-25+khumani+iron+mine+kwh&cd=5&hl=en&ct=clnk&gl=us&client=firefox-a.*

EMT-India, 2009, Manganese Ore Limited: EMT-India, last accessed October 13, 2010, at *http://www.emt-india.net/eca2008/AwardBooklet2008/19Mining.pdf.*

Outotec, 2010, Sintering technologies: Outotec, last accessed October 13, 2010, at *http://www.outotec.com/36252.epibrw.*

Saffy, Keith, 2003, Presentation to international manganese metal industry sustainable development conference in Chongqing, October 2003, *in* International Manganese Metal Industry Sustainable Development Conference, Chonqing, China, October 2003, Proceedings: Chonqing, China, International Manganese Metal Industry Sustainable Development Conference, last accessed October 13, 2010, at *http://www.mmc.co.za/downloads/International%20EIMn%20Sustainable%20Development%20Forum%202003%20Chongqing/06.Keith%20Saffy%20paper%20-%20english.pdf.*

SRK Consulting, 2010, Independent technical review of Project Kalahari: last accessed August 22, 2010, at *http://www.asx.com.au/asxpdf/20100706/pdf/31r5z91stzt9lb.pdf.*

Table 30. Estimated electricity requirements for producing ferronickel (FeNi) from calcined[1] nickel laterites using electric furnaces (kWh/t calcined feed).

[kWh/t, kilowatt hours per metric ton]

Country	Percent nickel in FeNi	Percent iron in FeNi	Estimated electricity consumption (kWh/t calcined feed)
Brazil	28	70	490
Colombia	35	64	520
Dominican Republic	37–40	50	379
Indonesia	25	65	480
Japan	19	80	460
New Caledonia	25	74	475
Ukraine	17	72	620
Estimated weighted world average	NA	NA	500

NA- Not available

[1] The calcining of nickel laterite ore involves the elimination of moisture (free and crystalline) remaining after the drying of laterite ore and oxidation of contained nickel. Most of the reductant required for this step is provided by combustion gases generated from burning coal. Electricity consumption for mining, drying, and calcining is primarily dependent on mine-plant design, efficiency of equipment used, ore composition and ore character (for example, grade and moisture content), and methods of transportation. A range of 10–15 kWh/t ore mined on a dry weight basis is probably a reasonable estimate. Free moisture content in laterite ores generally range from 25–35 percent and crystalline water content from 10–12 percent. Calculations per ton of ore can be roughly calculated applying these factors. Nickel recoveries in the smelters generally range from 88 to 97 percent.

References for Table 30

ALS Ammtec, 2011, Technical features, Comminution, Bond crushing work index: last accessed April 21, 2011, at *http://www.ammtec.com.au/public_panel/technical_features.php*.

Warner, A.E., Díaz,C.M., Dalvi, A.D., Mackey, P.J., and Tarasov, A.V., 2006, JOM world nonferrous survey, part III—Nickel—Laterite: Journal of Metals, v.58, no.4, p. 11–20, last accessed April 20, 2011, at *http://www.springerlink.com/content/7754881p3l34r875/*.

Table 31. Estimated electricity requirements for producing nickel from nickel laterite ores.

[kWh, kilowatt hours; t, metric ton; SX-EW, solvent extraction-electrowinning][1]

Process	kWh per unit	Units
Surface mining[2]	5	t ore (35% moisture by weight)
Drying, crushing, and grinding[3]	10–15	t dry ore
Pressure acid leaching	3,600	t recovered nickel
Refining (SX-EW)[4]	4,100	t recovered nickel

[1] Based on a nickel ore grade of 1 percent.

[2] Additional electricity may be required for activities that include belts for transport of ore, dewatering, and other types of equipment.

[3] The amount of electricity used to wash, dry, crush, and grind laterite ores depends on factors that include the clay fraction of ore, local climate, work Bond index, and size reduction requirements.

[4] Does not include cobalt recovery.

References for Table 31

Fittcock, John, E., 1993, Nickel and cobalt refining by QNI PTY Ltd., Yabulu, QLD: Mawby—AUSSIM Monograph, v. 19, last accessed April 28, 2011, at *http://www.ausimm.com.au/content/docs/mono19model_paper.pdf.*

Mayze, Richard, 1999, An engineering comparison of three treatment flowsheets in WA nickel laterite projects, *in* ALTA Nickel/Cobalt Pressure Leaching and Hydrometallurgy Forum, Jo-Al Enterprises, Melbourne, Australia, Proceedings: Melbourne, Australia, ALTA Nickel/Cobalt Pressure Leaching and Hydrometallurgy Forum, p. 1–19, also available at *http://batemanphp.syncrony.com/TECHNOLOGY/9June/An%20Engineering%20Comparision%20of%20the%203%20treatment%20flowsheets.pdf.*

Norgate, T.E., and Rankin, W.J., 2000, Life cycle assessment of copper and nickel production, *in* International Conference on Minerals Processing and Extractive Metallurgy, Melbourne, Australia, September 2000, Proceedings: Melbourne, Australia, International Conference on Minerals Processing and Extractive Metallurgy, p. 133–138, last accessed April 1, 2011 at *http://www.minerals.csiro.au/sd/CSIRO_Paper_LCA_CuNi.htm.*

Table 32. Estimated electricity requirements for producing ore, concentrate, matte and refined nickel from copper-nickel sulfide ore.
[kWh, kilowatt hours; t, metric ton]

Country, smelter or refinery technology, unit of feedstock type or product[1]	Estimated electricity consumption (kWh/unit
Botswana[2]	
Mining (per t nickel-copper ore mined)	45
Beneficiation (per t nickel-copper ore feedstock)	35
Conventional electric-arc furnace (per t of dry nickel-copper concentrate)	490–520
Flash furnace[3] (per t nickel-copper matte)	800
Brazil	
Fortaleza, flash furnace[3] (per t of dry nickel-copper concentrate)	103
Fortaleza, flash furnace[3] (per t of nickel-copper matte)	1,400
Canada	
Sudbury, electric-arc furnace (per t of dry nickel-copper concentrate)	440
Thompson, electric-arc furnace (per t of dry nickel-copper concentrate)	470
China	
Jinchuan, flash furnace[3] (per t of nickel-copper matte)	420
Finland	
Harjavalta, flash furnace[3] (per t of nickel-copper matte)	800
Harjavalta, flash furnace[3] (per t of nickel in matte)	2,600–2,800
Harjavalta refinery, electrowinning (per t of nickel)[4]	5,000–5,500
Russia	
Norilsky, electric-arc furnace (per t dry nickel-copper concentrate)	650
Pechanganickel, electric-arc furnace (per t of dry nickel-copper concentrate)	770
Nadezda, flash furnace[3] (per t of dry nickel-copper concentrate)	200
South Africa[5]	
Impala, electric-arc furnace (per t nickel-copper-PGM concentrate)	680
Lonmin, electric-arc furnace (per t nickel-copper-PGM concentrate)	700–900
Northam, electric-arc furnace (per t nickel-copper-PGM concentrate)	1,000
Polokwane, electric-arc furnace (nickel-copper-PGM matte), per t concentrate	750–850
Union-Mortimer, electric-arc furnace (per t nickel-copper-PGM concentrate)	820–850
Waterval, electric-arc furnace (per t nickel-copper-PGM concentrate)	750–850
Zimplats, electric-arc furnace (per t nickel-copper-PGM concentrate)	850–950
United States[5]	
Stillwater electric-arc furnace (per t nickel-copper-PGM concentrate)	900
Zimbabwe [5,6]	
Bindura electric-arc furnace (per t nickel-copper concentrate)	850–950
Bindura (electric-arc furnaces) (a) per t concentrate; (b) per t nickel-copper matte[5]	(a) 550–850; (b) 2,600–4,000
Bindura refinery, electrorefining (per t of recovered nickel)	2,500
General	
Beneficiation (crush, grind, float, dry, tailings placement, and other processes [per t nickel-copper concentrate])[7]	250–2,000
Slag cleaning, flash furnace (per t of slag)	50–100
Refining, electrorefining (per t of recovered nickel)	2,000–4,300
Sherritt-Gordon process, ammonia leach (per t of recovered nickel)	2,900

[1] Estimates for flash smelting may be underestimated in some cases. Estimates may not include grinding of coal, production of oxygen, handling of matte and other aspects of the facilities which cumulatively can be significant consumers of electricity. Also, some smelters recycle slag through the flash furnaces while others use dedicated electric furnaces for cleaning slag which consume electricity. Estimates for other plants may be applicable to the smelting process only and may not include electricity requirements for handling matte and materials, lighting, and other activities.

[2] Based on Phikwe, Selebi, and Selebi North. Mining uses cut and fill and open stoping. Smelting accomplished by Outokumpu flash technology with oxygen plant. Matte containing cobalt, copper, and nickel is exported for refining. Matte contains roughly 47 percent copper, 52 percent nickel and 1 percent cobalt. The electric-arc furnace, which received concentrates from the beneficiation plants at the Trojan and Shangani operations contained an average of roughly 9 percent nickel. The matte produced by the smelter contained about 20 percent nickel, 5 percent copper, and 1.20 percent cobalt. The converter matte contained about 70 percent nickel, 15 percent copper, and 1 percent cobalt. In 2011, the smelter was in a care and maintenance status.

[3] More than 75 percent of the electricity used in the post-beneficiation processes to produce matte associated with flash smelter technology is consumed in the slag-cleaning process.

[4] Includes electricity consumption burdened on a t of nickel for the leaching of matte and electrowinning to recover nickel, copper, and cobalt cathodes.

[5] The relatively high amounts of MgO associated with the ore minerals contained in concentrates requires higher smelting temperatures than most other metal sulfide concentrates and therefore consumes more energy, including electricity, per unit of metal recovered.

[6] Based on Bindura Nickel Corporation's Trojan operation. The grade and quality of the concentrate is reflected in a range of electricity requirements for the electric furnace from approximately from a low of 550 to a high of 850 kWh/t. Ore grades in the ore body are approximately 1 percent nickel that is upgraded to approximately 10 percent nickel through beneficiation. The concentrates require less energy to smelt than ores mined chiefly for their PGM content which have lower grades.

[7] The amount of electricity required for beneficiation on a unit recovered basis, concentrate or metal for example, is highly sensitive to ore grade and varies from mine to mine world-wide. Sulfide ore can contain from approximately 0.25 percent to over 2 percent nickel. Bond work index is also a significant factor that affects electricity consumption, but to a lesser extent than ore grade. Smelting of concentrates, when expressed against units of nickel, is greatly affected by metal content. Nickel concentrates with a low metal content are generally more refractory, produce more slag, and therefore generally require greater energy per unit of recoverable product. For some operations, such as those in South Africa derived from the Bushveldt Complex, the primary product is PGMs, while for others the primary products are copper and nickel. For example, ore produced from the Merensky Reef contains roughly 5–9 grams of PGM per t, 0.13 percent nickel, and 0.08 percent copper. The concentrates produced from these ores generally contain 2–4 percent nickel, 1.5–2.1 percent copper, and 130–150 grams of PGM per t.

References for Table 32

Alvarado, Sergio, Maldonado, Pedro, and Jaques, Iván, 1999, Energy and environmental implications of copper production: Science Direct, last accessed September 1, 2010, at *http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V2S-3W37P8P-4&_user=696292&_coverDate=04%2F30%2F1999&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1455024785&_rerunOrigin=google&_acct=C000038819&_version=1&_urlVersion=0&_userid=696292&md5=c289c37669656efe5f1435d24b429c2b&searchtype=a#toc4.*

Ausenco International Pty Ltd., 2005, Asian Mineral Resources Limited, Ban Phuc Nickel Mines Limited—Feasibility study: last accessed September 22, 2010, at *http://www.asianminres.com/Portals/1162/Documents/Feasibility_Nov05.pdf.*

Davenport, W.G., and Partelpoeg, E.H., 1987, Flash smelting—Analyses, control and optimization: New York, Pergamon Press, 324 p.

Dzingayi, E., 2006, Bindura Nickel Corporation smelter operations: The Journal of The South African Institute of Mining and Metallurgy, v. 106, p. 171–178, last accessed September 24, 2010, at *http://www.saimm.co.za/Journal/v106n03p171.pdf.*

Eckelman, M.J., 2010, Facility-level energy and greenhouse gas life-cycle assessment of the global nickel industry: Resources Conservation and Recycling, v. 54, 2010, p. 256–266, accessed September 3, 2010, at *http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6VDX-4XBP98M-1&_user=696292&_coverDate=02%2F28%2F2010&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1475959811&_rerunOrigin=google&_acct=C000038819&_version=1&_urlVersion=0&_userid=696292&md5=60f086100e8599bfdd742db95a252236&searchtype=a.*

Ecomaterials Center (Japan), 2003, Estimation of CO_2 emission and energy consumption in extraction of metals: National Institute for Materials Science, Independent Administrative Institution, last accessed June 7, 2011, at *http://www.nims.go.jp/imel/mde-report/Report/01-e-p.pdf.*

International Finance Corporation, 2007, Environmental, health, and safety guidelines—Base metal smelting and refining: International Finance Corporation, last accessed September 2, 2010, at *http://www.ifc.org/ifcext/sustainability.nsf/AttachmentsByTitle/gui_EHSGuidelines2007_SmeltingandRefining/$FILE/Final+-+Smelting+and+Refining.pdf.*

Kuck, P.H., 2009, Nickel [advance release]: U.S. Geological Survey, Minerals Yearbook 2007, v. I, p. 51.1–51.26, last accessed September 24, 2010, at *http://minerals.er.usgs.gov/minerals/pubs/commodity/ nickel/myb1-2007-nicke.pdf.*

Lewis, W.J., San Martin, A.J., Gowans, R. M., Lemieux, Michel, Primeau, Pierre, and Hardie, Colin, 2010, A preliminary assessment of the Dumont property Launay and Trécesson Townships, Quebec, Canada: Ontario Canada, Micon International Limited, last accessed February 3, 2011, at *http://www.royalnickel.com/docs/Sep2010_RNC_Dumont_43-101.pdf.*

Liddell, K.S., McRae, L.B., and Dunne, R.C., 1986, Process routes for beneficiation of noble metals from Merensky and UG-2 ores: Pyrometallurgy, last accessed June 9, 2011, at *http://www.pyrometallurgy.co.za/Mintek/Files/1986McRae.pdf*

Kumar, V., Pandey, B.D., and Akerkar, D.D., 1989, Electrowinning of nickel in the processing of polymetallic sea nodules: Hydrometallurgy, v. 24 (1990), p. 189–201.

Lagendijk, H., and Jones, R.T., 1997, Production of ferronickel from nickel laterites in a DC-arc furnace, *in* The Nickel-Cobalt 36th Annual Conference of Metallurgists, Sudbury, Canada, August 1997, Proceedings: Sudbury, Canada, The Nickel-Cobalt 36th Annual Conference of Metallurgists, last accessed September 22, 2010, at *http://www.mintek.co.za/Pyromet/Laterite/Laterite.htm.*

Matshameko, T.C., 2001, Preliminary investigation of energy conservation potential in the copper-nickel mining industry in Botswana: Strachclyde, Glascow, MSc thesis, submitted 2001, Department of Mechanical Engineering, Energy Systems Division, University of Strathclyde, Glascow, Scotland, 61 p., last accessed September 22, 2010, at *http://www.esru.strath.ac.uk/Documents/MSc_2001/thuso_matshameko.pdf.*

Mboma, A., and Chitaukire, D.K., 2011, Bindura Nickel Smelter from decommissioning, care and maintenance, to plant restart, *in* Jones, R.T. and den Hoed, P. (eds.), Southern African Pyrometallurgy 2011: Johannesburg, Southern African Institute of Mining and Metallurgy, p. 253–268, last accessed May 23, 2011, at *http://www.pyrometallurgy.co.za/Pyro2011/Papers/253-Mboma.pdf.*

Mobbs, P.M., 2010, Zimbabwe [advance release]: U.S. Geological Survey, Minerals Yearbook 2008, v. III, p. 43.1–43.6, last accessed September 22, 2010, at *http://minerals.er.usgs.gov/minerals/pubs/country/2008/myb3-2008-zi.pdf.*

Moskalyk, R.R., and Alfantzi, A.M., 2003, Review of copper pyrometallurgical practices—today and tomorrow: Minerals Engineering, v. 16, no. 10, p. 893–919.

Moyes, John, and Houllis, Frank, 2003, The development of the Intec Nickel Process to treat a low-grade Ni/Cu/Co/PGM concentrate: Intec China, last accessed September 28, 2010, at *http://www.intec-china.com/cn/UploadFile/news/2008_4_9_94051_134822.pdf.*

Mwana Africa, 2010, Bindura Nickel Corporation (BNC): Mwana Africa, last accessed February 3, 2011, at *http://www.mwanaafrica.com/oe/zim_bnc.asp.*

Nell, G.J., 2009, Milling technology selection for the Tati Activox® project base on pilot scale ultrafine milling test work on nickel sulphide concentrates, *in* Southern African Institute of Mining and Metallurgy Base Metals Conference 2009, Proceedings: Southern African Institute of Mining and Metallurgy Base Metals Conference

2009, last accessed September 24, 2010, at at *http://www.basemetals.org.za/Kasane2009/Papers/215-230_Nel.pdf.*

Newman, H.R., 2010, Botswana [advance release]: U.S. Geological Survey, Minerals Yearbook 2008, v. III, p. 5.1–5.7, last accessed September 22, 2010, at *http://minerals.er.usgs.gov/minerals/pubs/country/2008/myb3-2008-bc.pdf.*

Norgate, T.E., and Rankin, W.J., 2000, Life cycle assessment of copper and nickel production: Victoria, Australia, CSIRO Minerals, last accessed April 1, 2011 at *http://www.minerals.csiro.au/sd/CSIRO_Paper_LCA_CuNi.htm.*

Pandey, B.D., and Kumar, V., 1990, Extraction of copper and nickel from ammoniacal leach liquor of Indian Ocean sea nodules: Hydrometallurgy, v. 26 (1991), p. 35–45.

Pincock Perspectives, 2008, The processing of platinum-group metals (PGM)—Part 1: Pincock Perspectives, no. 89, 4 p., last accessed February 16, 2011 at *http://www.pincock.com/perspectives/Issue89-PGM-Processing-Part1.pdf.*

Rajput, R.K., 2006, Utilisation of electrical power: New Delhi, India, Laxmi Publication Ltd., 709 p., last accessed February 3, 2011, at *http://books.google.com/books?id=6z0wRsbPxI4C&pg=PA152&lpg=PA152&dq=kwh+nicken+refining&source=bl&ots=UazObM9a7x&sig=UtMqEY42S2nw6DiXIU21NOsbaxM&hl=ee&ei=Fg1KTeLLJ4j4swPRotjhCg&sa=X&oi=book_result&ct=result&resnum=1&sqi=2&vev=0CBMQ6AEwAA#v=onepage&q=kwh%20nickel%20refining&f=false.*

Riekkkola-Vanhanen, Marja, 1999, Finnish expert report on best available techniques in nickel production: Finnish Environmental Institute, last accessed June 14, 2011, at *http://www.ymparisto.fi/download.asp?contentid=10755&lan=en.*

Wang, Yanjia, and Chandler, William, 2009, The Chinese nonferrous metals industry—Energy use and CO_2 emissions: Science Direct, last accessed September 20, 2010, at *http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V2W-4W5M0GH-6&_user=696292&_coverDate=11%2F30%2F2010&_rdoc=1&_fmt=high&_orig=search&_origin=search&_sort=d&_docanchor=&view=c&_searchStrId=1472756072&_rerunOrigin=google&_acct=C000038819&_version=1&_urlVersion=0&_userid=696292&md5=d1c0f792bee8ab3dc0f4a6b22655508c&searchtype=a.*

Warner, A.E., Díaz, C.M., Dalvi, A.D., Mackey, P.J., Tarasov, A.V., and Jones, R.T., 2007, JOM world nonferrous smelter survey part IV—Nickel—Sulfide: Journal of Metals, v. 59, no. 4, p.58–72, also available at *http://www.springerlink.com/content/5556087g88376610/fulltext.pdf.*

Wolmarans, E., and Morgan, P. 2009, Milling circuit for Nkomati 375ktm concentrator, *in* Southern African Institute of Mining and Metallurgy Conference 2009, Proceedings: Southern African Institute of Mining and Metallurgy Conference 2009, last accessed August 5, 2010, at *http://www.basemetals.org.za/Kasane2009/Papers/269-290_Wolmarans.pdf.*

Yager, T.R., 2010, South Africa [advance release]: U.S. Geological Survey, Minerals Yearbook 2008, v. III, p. 37.1–37.22, last accessed September 20, 2010, at *http://minerals.er.usgs.gov/minerals/pubs/country/2008/myb3-2008-sf.pdf.*

Table 33. Estimated electricity requirements for production of ore from vertical crater retreat (VCR) mining.
[kWh/t, kilowatt hours per metric ton][1, 2, 3]

Process	Estimated mine electricity usage (kWh/t ore produced)	Percentage of total electricity use for mining
	Creighton, Canada	
Ventilation	99	60
Hoisting	33	20
Crushers, mining equipment, production drilling, and so forth.	33	20
Total	**165**	**100**

[1] Modeled after the Creighton nickel operation, Sudbury, Ontario, Canada. Ore production in 2007 was approximately 800,000 t. The Creighton operation may not be representative of other mines using VCR, a widely used bulk-mining method used in the Sudbury District, Canada. VCR is also referred to as panel mining.

[2] Except for standby generators, all power is supplied by a company-owned grid and provincial grid.

[3] Ore is loaded into trams pulled by diesel locomotives and delivered to an ore pass to feed an underground crusher. In other parts of the mine, ore is trucked up a ramp to a crusher. Ore is lifted to the surface in skips. Tailings are mixed with ash and cement then pumped underground as backfill. It is unclear if compressed air and backfilling are included in the estimate of electricity per t of ore. Mining activities are working at approximately 2,200 meters (7,000 feet) below the surface. Refrigeration of air is not necessary because during the warm months the ventilation system is directed through ice caverns that form in broken rock near the surface during the winter, an uncommon feature of mines. Refrigeration can consume significant amounts of electricity.

References for Table 33

Caterpillar Global Mining, 2008, Viewpoint, Perspectives on mining, Vale INCO's Creighton mine: Digging deeper by the day, no. 4, last accessed February, 8, 2011, at *http://www.cat.com/cda/files/1060444/7/Creighton_Eng.pdf*

Table 34. Estimated electricity requirements for loading of ore from a large open pit using primarily electric cable shovels and diesel-electric trucks at selected waste to ore ratios with an in-pit crusher and conveyor belt.

[kWh/t, kilowatt hours per metric ton][1]

Process	Feedstock	Waste to ore ratio	Product	Estimated mining, crushing, and belt requirements (kWh/t ore)
Open pit mining	Ore	1:1	Broken ore	3 [2,3]
Open pit mining	Ore	2:1	Broken ore	4 [2,3]
Open pit mining	Ore	3:1	Broken ore	5 [2,3]
In-pit crushing	Ore	N/A	Crushed ore	2–3[4]
Belt from in-pit crusher to mill	Crushed ore	N/A	Crushed ore	1[5]

Estimates rounded to nearest whole kWh/t ore, N/A – not applicable.

[1] Diesel-electric trucks convert fuel to electricity on-board and are not included in the estimates.

[2] Does not include pantograph assisted trucks, blast-hole drills, pumps, and other equipment that, outside of pantograph assisted trucks, combined require less than 1 kWh/t of ore.

[3] Based on P&H 4100c and 4100XPC electric rope shovels. P&H 2800XPC electric rope shovels are also used (see fig. 8). Some operations may select other electric shovels or non-electric equipment based on factors such as tons of ore and waste to be moved per unit of time, truck size, availability of electricity, geologic and engineering criteria pertaining to the geometry of the ore body and associated waste rock, availability of capital, and other factors. Electric shovels find their greatest application at high-tonnage operations, including coal, copper, gold, iron ore, and oil sand mines. For this model, cable shovels were estimated to operate at 50 percent of peak kilowatt draw and with an availability of over 95 percent. Roughly, 0.6–1.2 kWh/t of material moved is consumed by electric shovels; keep in mind that numerous factors affect electricity consumption, including moisture content, operating efficiency, rock breakage, and specific gravity. Waste to ore ratios also have a large effect when accounting for electricity consumption against ore mined.

[4] Electricity requirements will vary depending mostly on blasting (size of material broken), crusher type, Bond work index, and to what size the ore is crushed.

[5] Conveyor belts are used to transport ore from the crusher or offloading station to the mill. Crushers are not always located inside the pit. The conveyor belt was modeled at 1,600 meters in length, with a capacity of 10,000 t per hour and using 6,000 kW of power. Electricity consumption for conveyor belts depends on factors such as length, speed, tonnage capacity, and inclination of the belt. Conveyor belts are sometimes affixed with generators that produce electricity that can significantly offset the cost of the belt and other facility requirements. Not all mines use conveyor belts. Some use trains or trucks. See additional discussions relating to conveyor belts in table 3.

See Figure 9 for a photograph of a conveyor belt used to move ore from an in-pit crusher to a concentration facility.

References for Table 34

Chadwick, John, 2010, Material flow—Grasberg: International Mining, April 2010, last accessed September 22, 2010, at *http://www.infomine.com/publications/docs/InternationalMining/Chadwick2010n.pdf.*

Kennedy, B.A. (ed.), 1990, Surface mining (2nd ed.): Baltimore, MD, Society for Mining, Metallurgy, and Exploration, Inc., 1,197 p.

P&H MinePro Services, 2010, Operating specification, 2800XPC, Electric mining shovel, Digital drive control, accessed February, 11, 2011, at *http://www.phmining.com/MinePro/Literature/Spec/2800XPC.pdf.*

P&H MinePro Services, 2011, 4100XPC shovel, accessed August 8, 2011, at *http://www.phmining.com/en/PHMining/Mining-Equipment/Electric-Shovels/4100XPC.htm*. *http://www.phmining.com/MinePro/Literature/Spec/4100C.pdf.*

P&H MinePro Services, 2010b, 4100XPC electric mining shovel: P&H MinePro Services, Operating Specification XS-4189-1, PDF-0211, last accessed September 23, 2010, at *http://www.phmining.com/MinePro/Literature/Spec/4100XPC-Standard.pdf.*

Rio Tinto-Kennecott Utah Copper, 2010, Company website: Rio Tinto-Kennecott Utah Copper, last accessed August 4, 2011 at *http://kennecott.com/our-company/facts-about-our-operation/.*

Figure 8. A photograph of an electric rope shovel of the type used in large open pit mines. This mining shovel (P&H, model 2800XPC) has a nominal payload capacity of approximately 60 t in its 35 cubic meter-sized dipper and has seven motors. It is used primarily for loading 172–300 t capacity trucks. The shovel's maximum height is approximately 20 meters and weighs approximately 1,000 t (P&H, 2010). The unit is supplied with electricity by a cable (indicated by the black arrow in the photograph). Photograph is provided courtesy of Rio Tinto's Kennecott Utah Copper.

Figure 9. A segment of an 8 kilometer- (5 mile) long electrically-driven conveyor belt used to transport ore from the in-pit crusher at the Bingham Canyon Mine to the Copperton beneficiation plant (concentrator) in Utah, USA. See additional discussions relating to conveyor belts in table 3. Photograph is provided courtesy of Rio Tinto's Kennecott Utah Copper.

Table 35. Generalized electricity requirements for mining and preparing phosphate rock.
[kWh/t, kilowatt hours per metric ton]

Country/Process	Feedstock	Specific electricity usage (kWh/t product[1])
United States[2]		
Mining		
Mining with draglines (waste to ore ratio 1:1) and slurry pumping to beneficiation plant.	Phosphate rock	20–30
Mining with draglines (waste to ore ratio 2.5:1) and slurry pumping to beneficiation plant.	Phosphate rock	50
Beneficiation		
Crushing and grinding without flotation	Phosphate rock	10–20
Crushing and grinding with flotation	Phosphate rock	20–30
Estimated average for mining and beneficiation	**Phosphate rock**	**75**
Morocco		
Estimated average for surface mining and beneficiation	Phosphate rock	20–40 [3]
Estimated average for longwall mining and beneficiation	Phosphate rock	45
South Africa		
Mining Phalaborwa ores (Foskor) (previously known as Palabora)	Foskorite, tailings, and pyroxenite	<1
Other countries		
Burkina Faso, Tanzania, and Zimbabwe	Phosphate rock in Burkina Faso and Tanzania; carbonatite and minor guano in Zimbabwe	---[4]

[1] The amount of electricity used per t of phosphate rock mined and beneficiated is highly variable. Selection of equipment (loaders and trucks versus electric shovels, draglines, belts, and slurry lines) and waste to ore ratios are major determinants.

[2] TFI production cost survey for U.S. phosphate operations in 2003. The average comes from data collected from a survey of U.S. phosphate rock producers (except Monsanto) by the Fertilizer Institute in year ending December 31, 2003.

[3] Includes mining, crushing, screening, dewatering, and drying. Range in kWh/t is related to the waste-ore ratio, which can exceed 9:1. Electricity used in drying is relatively small. Drier heated with fuel. Model is based on a capacity of 3 million t per year of wet ore with a waste to ore ratio of 3.5:1 using 2 electric shovels and 6 draglines. Energy requirements for crushing and grinding can vary considerably based on size of material fed to the crusher, desired grinding size for optimum recoveries, mineralogy, Bond work index, and other factors.

[4] In the early 1980s, estimated electricity requirements at the Mingingu mine in Tunisia were 40 kWh/t of phosphate rock using surface mining, crushing, grinding, flotation, and concentrate thickening. In the early 1980s, estimated electricity requirements at the Dorowa mine in Zimbabwe were approximately 116 kWh/t of phosphate rock using surface mining, crushing, grinding, screening, flotation, and concentrate thickening and filtering.

Approximately 2/3 of production at the Company's mine is converted to phosphoric acid.

References for Table 35

Mhlongo, Henry, 2004, A perspective on the future development of the South African phosphate fertilizer industry, *in* 2004 IFA Production and International Trade Conference, Dubai, UAE, 3–5 October 2004, Proceedings: Dubai, UAE, 2004 IFA Production and International Trade Conference, last accessed August 4, 2011 at *http://www.fertilizer.org/ifacontent/download/6492/103248/version/1/file/2004_PIT_Mhlongo_Paper.pdf.*

Mining-technology.com, 2010, Benguérir Phosphates Mine, Morocco: Net Resources International, last accessed September 26, 2010, at *http://www.mining-technology.com/projects/benguearir/.*

Muehlberg, P., Reding, J., and Sheperd, B., 1977, The phosphate rock and basic fertilizer materials industry, *in* Industrial process profiles for environmental use: U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory, last accessed August 8, 2011 at, *http://nepis.epa.gov/Exe/ZyNET.exe/2000ZRGC.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1976+Thru+1980&Docs=&Query=600277023V%20or%20Industrial%20or%20process%20or%20materials%20or%20profiles%20or%20for%20or%20environmental%20or%20use%20or%20Chapter%20or%20The%20or%20phosphate%20or%20rock%20and%20basic%20or%20fertilizer%20or%20industry&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=pubnumber^%22600277023V%22&QFieldYear=&QFieldMonth=&QFieldDay=&UseQField=pubnumber&IntQFieldOp=1&ExtQFieldOp=1&XmlQuery=&File=D%3A\zyfiles\Index%20Data\76thru80\Txt\00000007\2000ZRGC.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h|-&MaximumDocuments=10&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=p|f&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL.*

United Nations Development Organization (UNIDO) and International Fertilizer Development Center (IFDC), 1998, Fertilizer manual: The Netherlands, Kluwer Academic Publishers, 615 p.

United Nations Environment Programme and the International Fertilizer Industry Association, 1998, Mineral fertilizer use and the environment: Fertilizer.org, 53 p., last accessed April 5, 2011, at *www.fertilizer.org/ifacontent/download/5407/85160/version/1/file/IFA-UNEP-Use.pdf.*

U.S. Department of Energy, 2002, Phosphates, *in* Energy and environmental profile of the U.S. mining industry: U.S. Department of Energy, last accessed September 22, 2010, at *http://www1.eere.energy.gov/industry/mining/pdfs/phosphate.pdf.*

Van Straaten, Peter, 2002, Rocks for crops—Agrominerals of sub-Saharan Africa: Nairobi, Kenya, International Center for Research in Agroforestry, 338 p., also available at *http://www.uoguelph.ca/~geology/rocks_for_crops/.*

Zellars-Willams, Inc., 1988, Assessment of present phosphate mining and beneficiation practice and evaluation of alternative technology: Florida Institute of Phosphate Research, 277 p., last accessed September 26, 2010, at *http://www1.fipr.state.fl.us/fipr/fipr1.nsf/129fc2ac92d337ca85256c5b00481502/e8a4a2ab4ea0fcf285256b2f0055f5c5/$FILE/04-031-068Final.pdf.*

Table 36. Estimated electricity requirements for the production of phosphoric acid-based products.
[kWh/t, kilowatt hours per metric ton]

Process/Location	Feedstock	Estimated electricity usage (kWh/t product[1,2])
Wet process/United States	Phosphate rock	134–138 (194–198 if H_2SO_4 produced on site)
Wet process/United States (mining through acid production)	Phosphate rock	210 (270 if H_2SO_4 produced on site)
Wet process/Florida)	Phosphate rock	152 (212 if H_2SO_4 produced on site)
Wet process/Europe	Phosphate rock	120–180[3] (185–245 if H_2SO_4 produced on site)
Wet process/Richard's Bay, South Africa	Foskorite and pyroxenite	287[4]
Wet process/Rustenberg, South Africa	Foskorite and pyroxenite	188[5]
Wet process/Morocco	Phosphate rock	278[6]
Wet process/Zimbabwe	Carbonatite	244 (309 if H_2SO_4 was generated on site)

[1] In addition to the variable types of technologies employed, electricity requirements can vary because of numerous factors that include ore grades and ore characteristics, crushing and grinding specifications, plant operating efficiencies , and economies of scale. Some operations produce reagent while others purchase them from vendors. Roughly 15 kwh/t of phosphoric acid is required for the production and transport of slurry to a processing plant.

[2] Using 22.4 kWh/t of sulfuric acid and a ratio of sulfuric acid to P_2O_5 of 2.5–3.15 with a median of 2.87, the electricity requirements to produce sulfuric acid per t of P_2O_5 ranges from 56 kWh–71kWh with a median of 65kWh. Approximately 2.8–3.6 t of phosphate rock with a median of 3.2 t are required to produce one t of P_2O_5 .

[3] The lower estimate is based on the assumption that grinding is not required. The higher estimate is based on grinding required to meet customer specifications. It was assumed that acid was purchased. Values in parentheses represent an additional 65kWh/t if sulfuric acid is manufactured on site.

[4] Feedstock from Phalaborwa consists of mill tailings that were previously crushed and ground. Other feedstock is crushed and ground at the phosphoric acid plants. A large portion of the facility's tailings and rock production is shipped to Richard's Bay for the production of phosphoric acid. The town site of Richard's Bay may generate all or a portion of the plant's electrical power requirements. Richard's Bay produces its own sulfuric acid in separate plants specifically to supply its phosphoric acid plants. The electricity requirement for acid production is included in the estimate.

[5] Rustenberg uses material from Phalaborwa as a way of using excess sulfuric acid from Rustenburg's smelter and at the same time produce a saleable product. The electricity required for sulfuric acid generation was not burdened on the phosphoric acid.

[6] Morocco's plants produce their own sulfuric acid. The additional electricity requirement of 65 kWh/t P_2O_5 is included in the estimate. Approximately 1/3 of the electricity requirements for the Jorf Lasfar (Morocco) operation may be generated on site. Multiple products are produced and may include sulfuric acid, concentrated and standard phosphoric acid, and fertilizer.

References for Table 36

El Azrak, A., and Bourgot, Alain, 1998, Expansion at Jorf Lasfar, Morocco—A new 1,000 tpd P_2O_5 unit: International Fertilizer Association, last accessed September 19, 2010, at *http://docs.google.com/viewer?a=v&q=cache:qfFmXKbNT1sJ:www.fertilizer.org/ifacontent/download/5401/85052/version/1/file/1998_ifa_marrakech_elazrak.pdf+El+Azrak,+A,+Bourgot,+Alain,+1998,+Expansion+at+Jorf+Lasfar,+Morocco&hl=en&gl=us&pid=bl&srcid=ADGEEShbEJKH13d2P6LcivH9zrLTFipqKs4FTHLvSdMbQcZpXowTWjbVee05aDEYnEPA0sRxzyS_IusktPSg_izC2y095TLQia1FCzqCCJgusjkpYEEqJ5s7pZe1hUsngojVIaJf5w5d&sig=AHIEtbTFvP7j6sgR2bpNKP1EGLXVMuQveQ.*

European Fertilizer Manufacturers Association, 2000, Production of phosphoric acid, *in* European Fertilizer Manufacturers Association (ed.), Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry: Brussels, Belgium, European Fertilizer Manufacturers Association, booklet no.4

of 8, 48 p., last accessed April 6, 2011, at *http://www.efma.org/documents/file/bat/BAT%20Production%20of%20Phosphoric%20Acid.pdf.*

Florida Industrial and Phosphate Research Institute (FIPR), 2010, Mining and beneficiation: Florida industrial and phosphate research institute, last accessed June 9, 2011, at *http://webcache.googleusercontent.com/search?q=cache:2zZ2qoY_qJIJ:www.fipr.state.fl.us/research-area-mining.htm+kwh&cd=7&hl=en&ct=clnk&gl=us&source=www.google.com*

Foskor (Pty) Ltd., 2011, Acid division—Richards Bay: Foskor, last accessed April 6, 2011 at *http://www.foskor.co.za/ob_richards_bay.php.*

Megy, J.A. 2008, Improved hard process—Best available technology for producing high grade phosphoric acid from Lower Zone phosphate ore in the Florida Southern Extension, *in* 23rd Annual Regional Phosphate Conference, Lakeland, Florida, October 8–9, 2008, Proceedings: Lakeland, Florida, 23rd Annual Regional Phosphate Conference, last accessed September 26, 2010, at *http://www.phosphatesustainability.com/pdfs/Improved_Hard_Process_Present.pdf.*

Mhlongo, Henry, 2004, A perspective on the future development of the South African phosphate fertilizer industry: Fertilizer.org, last accessed September 19, 2010, at *www.fertilizer.org/ifa/layout/set/print/content/view/full/8559/.../10.*

The Fertilizer Institute, 2004, Production cost survey for the year ended December 31, 2003: The Fertilizer Institute, Washington, DC, limited access at *http://www.tfi.org/members/secureDocument.cfm?docID=75*.

United Nations Environment Programme and the International Fertilizer Industry Association, 1998, Mineral fertilizer use and the environment: Fertilizer.org, 53 p., last accessed April 5, 2011, at *www.fertilizer.org/ifacontent/download/5407/85160/version/1/file/IFA-UNEP-Use.pdf*

United Nations Industrial Development Organization (UNIDO) and International Fertilizer Development Center (IFDC), 1998, Fertilizer Manual: The Netherlands, Kluwer Academic Publishers, International Fertilizer Center, 599 p., last accessed September 26, 2010, at *http://books.google.com/books?id=qPkoOU4BvEsC&pg=PR4&lpg=PR4&dq=Fertilizer+Manual,+UNIDO,+Int%E2%80%99l+Fertilizer+Center&source=bl&ots=dGHGIl3jRW&sig=CAV85r6D-.AuJ3ptpInyAMZDvO08&hl=en&ei=7L05TY3VHIL98AaumsTWCg&sa=X&oi=book_result&ct=result&resnum=1&ved=0CBMQ6AEwAA#v=onepage&q&f=false*.

Van Straaten, Peter, 2002, Rocks for crops—Agrominerals of sub-Saharan Africa: Nairobi, Kenya, International Center for Research in Agrofoerstry, 338 p., also available at *http://www.uoguelph.ca/~geology/rocks_for_crops/.*

Table 37. Estimated electricity requirements for the production of platinum-group metals (PGM).
[kWh/kg, kilowatt hour per kilogram]

Country	kWh/kg recoverable PGM[1]
Botswana	21,400
South Africa	23,300
Zimbabwe	21,400

[1]The estimates include all of the process steps (mining, air ventilation and refrigeration, compressors, crushing, and water pumps), concentration (milling, flotation, tailings handling, and pumps), smelting furnaces, flash dryers, matte handling, and refining (matte-leaching, tank house, compressors, and boilers). Actual electricity consumption per unit can vary considerably, owing to the significant range in grades of ore (roughly 3–8 g/t) and resulting concentrates (100–400 g/t).

Metals that include cobalt, copper, gold, and nickel are also being produced as co- or byproducts in the facilities that treat sulfide ores. Electricity requirements for smelters range from approximately 600–855 kWh/t concentrate.

References for Table 37

Cramer, L.A., 2001, The extractive metallurgy of South Africa's platinum ores: Journal of Metals, v. 53, no. 10, p. 14–18.

Implats, 2007, Corporate responsibility report 2007: Implats, last accessed September 28, 2010, at *http://www.implats.co.za/cr/reports/2007/env.htm#performance*.

Jones, R.T., 2005, An overview of Southern African PGM smelting: Mintek, Private Bag X3015, Randburg, 2125, South Africa, 32 p., last accessed September 28, 2010, at *http://www.mintek.co.za/Pyromet/Files/2005JonesPGMsmelting.pdf.*

Loferski, P.J., 2010, Platinum-group metals [advanced release]: U.S. Geological Survey, Minerals Yearbook 2008, v. I, p. 51.1–51.26, last accessed September 29, 2010, at *http://minerals.er.usgs.gov/minerals/pubs/commodity/platinum/myb1-2008-plati.pdf.*

Mabiza, L., 2006, An overview of PGM smelting in Zimbabwe—Zimplats operations, *in* Jones, R.T. (ed.), Southern African Pyrometallurgy 2006: Johannesburg, South African Institute of Mining and Metallurgy, p. 63–76, last accessed September 28, 2010, at *http://www.pyrometallurgy.co.za/Pyro2006/Papers/063_Zimplats.pdf.*

Matshameko, T.C., 2001, Preliminary investigation of energy conservation potential in the copper-nickel mining industry in Botswana: Starchclyde, Glascow, MSc thesis, submitted 2001, Department of Mechanical Engineering, Energy Systems Division, University of Strathclyde, Glascow, Scotland, 61 p., last accessed September 19, 2010, at *http://www.esru.strath.ac.uk/Documents/MSc_2001/thuso_matshameko.pdf.*

Mobbs, P.M., 2010, Zimbabwe [advance release]: U.S. Geological Survey, Minerals Yearbook 2008, v. III, p. 43.1–43.6, last accessed September 19, 2010, at *http://minerals.er.usgs.gov/minerals/pubs/country/2008/myb3-2008-zi.pdf.*

Newman, H.R., 2010, Botswana [advance release]: U.S. Geological Survey, Minerals Yearbook 2008, v. III, p. 5.1–5.7, last accessed September 19, 2010, at *http://minerals.er.usgs.gov/minerals/pubs/country/2008/myb3-2008-bc.pdf.*

Reinier, De Man, 2007, Sustainable platinum—Consultant report: The Netherlands, Reinier De Man, Leiden, 26 p., last accessed October 6, 2010, at *http://www.rdeman.nl/platinum/download/papersRT2/AngloP-Petersen.pdf.*

Rule, C.M., 2009, Energy considerations in the current PGM processing flow sheet utilizing new technologies: The Journal of the Southern African Institute of Mining and Metallurgy, v. 108, p. 39–46, last accessed October 6, 2010, at *http://saimm.server291.com/Journal/v109n01p039.pdf.*

Van Manen, P.K., 2009, Furnace energy efficiency at Polokwane smelter: Journal of the South African Institute of Mining and Metallurgy, v. 108, no. 1, p. 47–52.

Yager, T.R., 2010, South Africa [advance release]: U.S. Geological Survey, Minerals Yearbook 2008, v. III, p. 37.1–37.22, last accessed September 23, 2010, at *http://minerals.er.usgs.gov/minerals/pubs/country/2008/myb3-2008-sf.pdf.*

Table 38. Estimated electricity requirements for the production of platinum from the Merensky Reef and UG2 low-grade open pit in South Africa.

[kWh/t, kilowatt hours per metric ton; PGM, platinum-group metals; kWh/oz, kilowatthours per troy ounce]

Product and Process	Feedstock	Product(s)	Estimated mine, beneficiation, and other onsite requirements for electricity usage (kWh/t ore, concentrate, and per ounce platinum)[1]
Open pit mining	PGM ore	PGM ore	Less than 1 kWh/t ore
Beneficiation and other onsite requirements	PGM ore	Concentrate	70 kWh/t ore treated
Beneficiation and other onsite requirements	PGM ore	Concentrate	700 kWh/oz. recoverable platinum in ore treated
Beneficiation and other onsite requirements	PGM ore	Concentrate	2,100 kWh/t concentrate
Beneficiation and other onsite requirements	PGM ore	Concentrate	730 kWh/oz. recoverable platinum in concentrate

[1]Estimates are based on published information pertaining to the development of open pits scheduled to produce ore at the Pilanesberg deposits in South Africa. The ore production was estimated at 365,000 t per month (waste to ore ratio is 6.5:1). Nearly all mining equipment will be diesel-powered loaders and trucks, so electricity consumption is low per t of ore. The beneficiation plant's design is likely similar to others with primary crushing into a semi-autogenous grinding (SAG) mill with mill-float- mill-float (MF2) circuit and ultra-fine grinding on the combined cleaner tail streams. UG2 and Merensky Reef ores require separate plants. A dense media separation is also installed. The electrical power for the operations was estimated at 40MVA. Note that the electricity requirement per ounce of recoverable platinum for beneficiation is relatively high compared to other PGM operations, owing to the low grade of ore. The estimate of 700 kWh/troy oz for ore containing 2.7 g/t of platinum was developed through proportioning of platinum in ores mined in several major South African operations. A platinum recovery of 85 percent was assumed. It was estimated that approximately 30 t of ore yields 1 t of concentrate containing roughly 200 gm of PGM, 90 gms of which was platinum. Energy requirements for crushing and grinding can vary considerably based on size of material fed to the crusher, desired grinding size, Bond work index, and other factors. The grades of ore and concentrate are significant factors when expressing energy consumption against recovered metals.

References for Table 38

Harper, F., and de Witt, D.R., 2009, National Instrument T 43-101—Technical report and valuation statement for Pilanesberg Platinum Mines (PPM) Northwest Province, South Africa, for Platmin Limited (Platmin): Sandton, South Africa, Venmyn, last accessed September 19, 2010, at *http://www.platmin.com/im/files/reports/CPR_pilanesberg_mar09.pdf*.

Jones, R.T., 1999, Platinum smelting in South Africa: South African Journal of Science, v. 95, p. 525–534, last accessed May 19, 2011, at *http://www.mintek.co.za/Pyromet/Platinum/Platinum.htm.*

Mbendi Information Services, 2008, Platmin receives mining right for Pilanesberg project: Mbendi, last accessed September 19, 2010, at *http://www.mbendi.com/a_sndmsg/news_view.asp?I=90304&PG=154.*

Mining Weekly, 2007, Pilanesberg project gets go-ahead, smelter and JSE on radar: Mining Weekly, last accessed September 20, 2010, at *http://www.miningweekly.com/article/pilanesberg-project-gets-goahead-smelter-and-jse-listing-on-radar-2007-07-27.*

Mining Weekly, 2008, Platinum-miner reaching deep: Mining Weekly, last accessed September 20, 2010, at *http://www.miningweekly.com/article/platinumminer-reaching-deep-2008-08-22*.

SRK Consulting, 2007, Definitive feasibility study on the exploitation of the Ruighoek and Tuschenkomst properties: Centurion, South Africa, Platmin Limited, SRK Project Number 376482, last accessed September 19, 2010, at *http://www.platmin.com/p/files/tr/ruighoek_tuschendkomst_SRK_fs_07aug07.pdf.*

Table 39. Estimated electricity requirements for production of platinum from PGM ore by conventional breast-stoping, room and pillar, and hybrid mining of Merensky Reef and UG2 ores, South Africa.
[kWh/t, kilowatt hours per metric ton; kWh/oz, kilowatt hours per troy ounce; PGM, platinum-group metals]

Product and Process	Feedstock	Product	Estimated mine and beneficiation plant electricity usage (kWh/t ore or per ounce recovered platinum [Pt])
General [1,2,3]			
Underground mining and processing	PGM ore	Concentrate	100–250 kWh/t ore
Underground mining and processing	PGM ore	Concentrate	800 kWh/oz Pt in concentrate
Underground mining [4]	PGM ore	Ore	120 kWh/t ore
Beneficiation [5]	PGM ore	Concentrate	50 kWh/t ore
Smelting (electric furnace)[6]	PGM concentrate	PGM matte	600–1,100 kWh/t concentrate
Anglo Platinum Limited Group[7]			
Mining (includes hoists, dewatering, ventilation, and refrigeration)	--	PGM ore	50 kWh/t ore milled; 780 kWh/oz refined Pt
Beneficiation (includes crushing and grinding, flotation, and tailings treatment)	PGM ore	PGM concentrate	40 kWh/t ore milled ; 570 kWh/oz refined Pt
Smelting (electric furnaces, dryers, and converters)	PGM concentrate	PGM matte	33 kWh/t ore milled ; 520 kWh/t/oz refined Pt
Refining PGM (Leach, tank house, and required purification steps)	PGM matte	Refined PGM	6.0 kWh/t ore milled ; 100 kWh/oz refined Pt
Total of Anglo Platinum Limited Group[8]	--	--	**130 kWh/t ore milled ; 2,000 kWh/oz refined Pt**
Northam Mining Limited[9]			
Production	PGM ore	PGM ore	60–70 kWh/t ore milled; 800 kWh/oz refined Pt
Pumping (dewatering)	PGM ore	PGM ore	50 kWh/t ore milled; 500 kWh/oz refined Pt
Ventilation	PGM ore	PGM ore	20 kWh/t ore milled; 200 kWh/oz refined Pt
Refrigeration	PGM ore	PGM ore	30 kWh/t ore milled; 300 kWh/oz refined Pt
Lighting	PGM ore	PGM ore	2–3 kWh/t ore milled; 20 kWh/oz refined Pt
Beneficiation	PGM ore	PGM concentrate	30 kWh/t ore milled; 300 kWh/oz refined Pt
Post-beneficiation (smelting [electric furnaces] and refining)	PGM concentrate	Precious and base metals	40 kWh/t ore milled; 400 kWh/oz refined Pt
Total of Northam Mining Limited	--	--	**200 kWh/t ore milled; 2,500 kWh/oz refined Pt.**

[1] Two main shafts, 980 meters in depth. Estimated ore production at 230,000 t/mo (ton per month). Ore is transported using trackless tramming with trucks, underground crushing, hoisting ore at 26 days/mo (days per month) and 18 hours/day. Pneumatic scrapers are used mostly for the ores of the Merensky Reef, and load-haul dumps (LHDs) are used mostly for mining the ores of the UG2. Ventilation air is cooled. Plant design includes primary underground one-stage crushing into a semi-autogenous (SAG) mill with mill-float- mill-float (MF2) circuit and ultra-fine grinding on the combined cleaner tail streams. Lower electricity requirement developed from estimate for the Frischgewaagd-Ledig Core mine and processing with 40MVA power feed. At 90 percent efficiency = 280 million kWh/annum. Estimate for kWh/oz Pt developed through proportioning of PGM in ore and applies to the Frischgewaagd-Ledig Core mine and mill in South Africa. Underground mining at Northam uses hydropower (high-

pressure water) instead of fuel or electrically operated equipment for major underground equipment. They require more electricity and less fossil fuel per t of ore, but have the advantage of generating less heat and exhaust. Mines are between 700 meters (Frischgewaagd-Ledig Core mine) and 2,200 meters (Northam) in depth, which contributes significantly to the differences in electricity requirements. Kennedy's Vale project is planned for mining between 600 meters and 1,600 meters in depth. The electricity consumption for mining was estimated at 82 kWh/t of ore as per published evaluation. This estimate may be low because the mine was assessed using fresh air instead of refrigerated air. Fans and refrigeration are major users of electricity.

[2] Crushing and grinding kWh/t requirements can vary significantly for UG2 and Merensky Reef ores. They depend on proportions of ores, size of material fed to crushers, and target grind size. Beneficiation estimates range from approximately 30kWh/t–70 kWh/t of feed. An exception was the estimate for Kennedy's Vale, which was 90 kWh/t of mill feed and included treatment and placement of tails and other minor items.

[3] Combined kWh estimate for Kennedy's Vale for comparison purposes is 172 kWh/t ore for mining, processing, tailings treatment and placement, and other minor requirements.

[4] Based on Royal Bafokeng Resources' mines. Mining is primarily room and pillar. Mine depth is approximately 700 meters; ventilation and compressed air are required. No mention of refrigeration of air is in the source information.

[5] Includes: ore receipt, Merensky Reef and UG2 storage and blending, crushing and screening, primary milling and flotation, rougher flotation, secondary milling and tertiary stirred mill grinding, and tailings thickening and deposition. An additional burden was added for tailings management. Additional electricity requirements for housing and other ancillaries are not included in the estimates.

[6.] Electrical power consumption for electric furnaces per t of concentrate. The lower value of the Bindura range applies to concentrates derived from ores mined from the Merensky Reef and the high end of the range is the electricity required to smelt the concentrate derived from ores mined from the UG2. The lower sulfide mineral content and the higher MgO, SiO_2, and Al_2O_3 content in UG2 concentrate is more refractory and requires more energy to smelt than ores in the Merensky Reef, but because UG2 concentrates contain up to twice the amount of PGMs than the Merensky Reef concentrates, the actual electricity required per unit of recovered PGM is lower. The electricity required to smelt blended concentrates relies to some extent on the relative proportions of the feedstock.

[7] Includes the Amandelbult Section (underground), Bafokeng Rasimone mine (underground), Kroondal (underground with minor pit production), Mogalakwena Section (formerly known as the Potgietersrust open pit mine), Rustenburg mines (underground), and the Union Section (underground). Also includes production from recovery and reprocessing of tailings (surface); there is a possibility that other operations are included. In 2006, the average "4E" (platinum, palladium, rhodium, and gold) ore grade for the mines was approximately 3.6g/t and approximately 44 Mt of ore was processed through the mills with approximately 2.8Moz (million troy ounces) of refined platinum, plus additional PGM, copper, gold, and nickel recovered. Underground mining operations average about 1,400 m below surface. Over 90 percent of platinum-group metal production originates from underground operations. Approximately 80 percent of the operations' energy requirements are met by electricity. In addition to power purchased from Eskom's grid, some additional power is generated on site by hydropower (approximately 4,500 kw). Electricity consumption for separating and recovering refined or intermediate products containing palladium, rhodium, gold, copper, and nickel are burdened on refined platinum.

[8] Total rounded to two significant figures.

[9] Includes only Northam Platinum Limited's Zondereinde mine. Average mining depth is about 1,800 meters. Estimate based partly on using a 90 percent power conversion factor from MVA to kWh and estimates for hours of use per operational unit. A portion of the concentrate produced at the plant is exported for smelting and refining or sold on site. Estimates are rounded to one significant figure. Electricity consumption for separating and recovering refined or intermediate products containing palladium, rhodium, gold, copper and nickel are burdened on refined platinum.

References for Table 39

Mabiza, L., 2006, An overview of PGM smelting in Zimbabwe—Zimplats operations, *in* Jones, R.T. (ed.), Southern African Pyrometallurgy 2006: Johannesburg, South African Institute of Mining and Metallurgy, p. 63–76, last accessed September 28, 2010, at *http://www.pyrometallurgy.co.za/Pyro2006/Papers/063_Zimplats.pdf.*

Northam Platinum Ltd., 2009, Technical Overview—Northam Mine: accessed September 20, 2010, at *http://www.northam.co.za/b/files/technical_overview_aug09.pdf.*

Northam Platinum Ltd., 2010, Technical Overview 2009—Zondereinde Mine: Northam Plantinum Ltd., last accessed September 20, 2010, at *http://www.northam.co.za/business/files/technical_overview.pdf.*

Northam Platinum Ltd., 2010, Sustainable development report 2010: Northan Platinum Ltd., last accessed September 20, 2010, at *http://www.northam.co.za/sd/reports/2010/environment.htm.*

Pincock, Allen, & Holt, 2008, The processing of platinum group metals (PGM)—Part 1: Pincock Perspectives, no. 89, last accessed May 20, 2011, at *http://www.pincock.com/perspectives/Issue89-PGM-Processing-Part1.pdf.*

Pincock, Allen, & Holt, 2008, The processing of platinum group metals (PGM)—Part 2: Pincock Perspectives, no. 90, last accessed May 20, 2011, at *http://www.pincock.com/perspectives/Issue90-PGM-Part2.pdf.*

Royal Bafokeng Platinum Ltd., 2011, Bafokeng Rasimone platinum mine: Royal Bafokeng Platinum Ltd., last accessed May, 9, 2011, at *http://www.bafokengplatinum.co.za/b/o_i.php.*

RSG Global, 2006, Kennedy's Vale Project, South Africa: Eastern Platinum Limited, last accessed September 20, 2010, at *http://www.eastplats.com/_resources/reports/Kenn_May_07.pdf*, an earlier version of the report is available at *http://www.eastplats.com/_resources/reports/Kennedy_Vale_Project-TechReport.pdf.*

Rule, C.M., 2008, Energy considerations in the current PGM processing flow sheet utilizing new technologies, *in* Third International Platinum Conference, Platinum in Transformation, The Southern African Institute of Mining and Metallurgy, Sun City, South Africa, October 5–9, 2008: Sun City, South Africa, Third International Platinum Conference, Platinum, last accessed August 8, 2011 at *http://www.platinum.org.za/Pt2008/Papers/045-52_Rule.pdf* .

Snowden Mining Industry Consultants Limited, 2010, Competent persons' report on the mineral assets of Royal Bafokeng Platinum Ltd.: Royal Bakofeng Platinum, last accessed August 4, 2011, at *http://www.bafokengplatinum.co.za/im/files/listing/rbplat_pls_oct2010.pdf*

Tshisekedi, Jean Rene, 2008, Energy consumption standards and costs in South African gold and platinum mines: Masters of Science Thesis, University of the Witwatersrand, South Africa, last accessed May 6, 2011, at *http://wiredspace.wits.ac.za/handle/10539/7043.*

Wesizwe Platinum Ltd., 2008, Bankable feasibility study on the exploitation of the Frischgewaagd-Ledig Core Project Area: Wesizwe, last accessed September 23, 2010, at *http://www.wesizwe.co.za/downloads/presentations/BFS_Overview.PDF.*

Table 40. Generalized estimated electricity requirements for mining and processing potash (K_2SO_4) ore by conventional underground room and pillar method and solution mining.

[kWh/t, kilowatt hours per metric ton]

Generalized mining and processing methods	Feedstock	Product	Electricity requirement (kWh/t)
Mechanized room and pillar[1]	Primarily sylvite (KCl) with halite (NaCl)	Ore	35–60[2] (Avg. of 9 Canadian operations approx. 41)
Solution mining/surface crystallization plant	Sylvite, halite, and or carnalite brines	Potash	200–400
Conventional crushing, scrubbing, sizing, flotation, de-brining, and drying[2]	Primarily sylvite (KCl) with halite (NaCl)	Potash	55–120[4] (Avg. of 8 Canadian operations approx. 80kWh/t)
Mechanized room and pillar, calcining, dissolution, solar evaporation, collection, and drying.	Polyhalite ($K_2Ca_2Mg(SO_4)^4{\cdot}2(H_2O)$)	Potash	150

[1] Mining at average depths of roughly 1,000 meters. Most underground electricity consumption includes mining equipment, pumping, shaft services, and ventilation requirements.

[2] Does not include the crystallization process, which relies mostly on natural gas.

References for Table 40

GENIVAR, 2006, MagIndustries Corporation—Phase I bankable feasibility study for two modules of 580,000 t per year potash plant in the Kouilou region of the Republic of Congo: Magindustries.com, last accessed September 20, 2010, at *http://www.magindustries.com/cmsdocs/Technical%20Reports/Final_report_rev_0_2_exec_ ssum.pdf.*

Gustavson Associates, 2010, Producing sulfate of potash from polyhalite with cost estimates, Prepared for IC Potash Corporation: IC Potash, last accessed May 24, 2011, at *http://www.icpotash.com/_resources/ICP_Production_ of_SOP_from_Polyhalite_White_Paper.pdf.*

Jones, R.T., 1999, Platinum smelting in South Africa: South African Journal of Science, v.95, p. 525–534, last accessed May 19, 2011, at *http://www.mintek.co.za/Pyromet/Platinum/Platinum.htm.*

Mining-technology.com, 2011, Rocanville Potash Mine, Saskatchewan, Canada: Mining-technology, last accessed September 20, 2010, at *http://www.mining-technology.com/projects/rocanville/.*

Natural Resources Canada, 2010, Energy benchmarking—Canadian potash production facilities benchmarking results: Natural Resources Canada, last accessed September 20, 2010, at *http://webcache.googleusercontent.com/search?q=cache:UPvNEi9mA00J:oee.nrcan.gc.ca/publications/infosource/pub/cipec/potash-production/benchmarking.cfm%3Fattr%3D20+solution+mining+kwh&cd=1&hl=en&ct=clnk&gl=us&client=firefox-at.*

Natural Resources Canada and Canadian Industry Program for Energy Conservation, 2003, Energy benchmarking—Canadian potash production facilities in cooperation with the Canadian Fertilizers Institute: Natural Resources Canada, last accessed September 20, 2010, at *http://oee.nrcan.gc.ca/publications/infosource/pub/cipec/potash-production/contents.cfm?attr=20.*

Perucca, Carlos, F., 2001, Potash processing in Saskatchewan—A review of process technologies: last accessed September 20, 2010, at *http://technology.infomine.com/hydrometmine/papers/Potash%20Processing %20in%20SK%20-%20A%20Review%20of%20Process%20Technologies.pdf.*

Potash Corporation of Saskatchewan Inc., 1996, Patience Lake Division: Canadian Industry Program for Energy Conservation, last accessed September 20, 2010, at *http://www.ghgregistries.ca/registry/out/C0761-PATIEN~1-DOC.PDF.*

Potash One Inc., 2010, Potash Legacy Project: K+S Potash Canada, last accessed September 20, 2010, at *http://www.potash1.ca/s/LegacyProject.asp.*

Table 41. Estimated electricity requirements for the production of silicon metal.
[kWh/t, kilowatt hours per metric ton]

Process	Feedstock	Estimated plant electricity usage (kWh/t silicon metal)
Open, closed, or semi-closed submerged electric-arc furnaces	Quartz sand, quartz, and/or quartzite	12,000–15,000[1]

[1] The lower range of the estimate represents silicon contents ranging from 96–99 percent in silicon metal. The higher value represents silicon metal that has been further processed through treatment by acid and other means to meet the specifications necessary for solar cell application (Hesse, 2009) and is of the highest purity of silicon—at least 98 percent. A proposed silicon metal plant in Labrador, Canada, was estimated to require approximately 12,000 kWh/t to produce a t of silicon from quartzite ore (approximately 5,000 kWh/t of quartzite treated) based on a requirement to supply 2.4 t of quartzite to produce one t of silicon metal (Government of Newfoundland and Labrador, Department of Mines and Energy, 2000). The South African Polokwane silicon plant, the largest silicon producer in South Africa, produces 45,000 t of silicon metal and 15,000 t of fume (Solidarity, 2010). Silica fume, composed of silicon dioxide, is a byproduct of producing silicon metal or ferrosilicon alloys. Silica fume is added to concrete mix to provide added strength (Silica Fume Association, 2011). The plant has three 65MW furnaces that process quartz-vein material as feedstock that is mined from the Witkop silica deposit located near the smelter. The Polokwane plant produces chemical grade and metallurgical grade silicon. Chemical grade silicon is about 98.5 percent silicon, 0.5 percent iron, 0.07 percent calcium, and 0.2 percent aluminum, whereas metallurgical grade silicon is at or greater than 98.50 percent silicon with a maximum content of 0.10 percent iron, 0.07 percent calcium, and 0.20 percent aluminum. A rough estimate of 11,500 kWh/t of silicon metal was estimated using a factor of 90 percent capacity availability for the three furnaces.

References for Table 41

Deutsche Bank Research, 2004, Research notes—Silicon as an intermediary between renewable energy and hydrogen: Deutsche Bank Research, working paper no. 11, last accessed September 20, 2010, at *http://www.dbresearch.com/PROD/DBR_INTERNET_EN-PROD/PROD0000000000079095.pdf.*

Elkem Solar AS, 2006, Elkem Solar AS, *in* Third silicon conference, München, Germany, 3 April 2006, Proceedings: München, Germany, Third silicon conference, PowerPoint presentation last accessed September 20, 2010, at *http://hugin.info/111/R/1087348/190414.pdf.*

European Commission, 2001, Integrated pollution prevention and control (IPPC) reference document on best techniques in the nonferrous metals industries: last accessed September 20, 2010, at *http://ceho.vuv.cz/CeHO/CeHO/Technologie/BREF_Non_ferrous_metals_final_1201.pdf*

Globe Specialty Metals, 2010, Silicon metal: Globe Specialty Metals, last accessed September 20, 2010, at *http://www.glbsm.com/product-information/Globe-Silicon-Metal.pdf.*

Government of Newfoundland and Labrador Department of Mines and Energy, 2000, Silicon metal smelter—The Labrador advantage: Newfoundland and Labrador Department of Natural Resources, last accessed September 20, 2010, at *http://www.nr.gov.nl.ca/mines&en/publications/geology/silicon.pdf.*

Hesse, K., 2009, Advanced solar-grade Si material, *in* Rhodes, W.T. ed., Springer series in optical sciences, v. 140, p. 45–55: Berlin, Germany, Springer-Verlag, abstract accessed September 20, 2010, at *http://www.springerlink.com/content/q5272739121u6856/.*

Semi, 2011, Metallurgical-grade silicon making inroads on PV: Semi, last accessed April 1, 2011, at *http://www.semi.org/en/IndustrySegments/Materials/p044005*.

Silica Fume Association, 2011,What is silica fume: Silica Fume Association, last accessed March 31, 2011, at *http://www.silicafume.org/general-silicafume.html.*

Solidarity, 2010, Solidarity refuses to accept wage offer by silicon smelters: Solidarity, last accessed September 20, 2010, at *http://www.solidaritysa.co.za/Home/wmview.php?ArtID=2454.*

Table 42. Estimated electricity requirements for electrorefining silver from solution.

[kWh, kilowatt hours][1]

Process	Feedstock/product	kWh/troy ounce refined silver[1]
Electrowinning	Cyanide solution of 100–1,000 ppm silver/Refined silver	0.3–0.03[2]
Electrowinning	Solution of nitric acid and silver nitrate silver; content NA/Refined silver	0.012–0.013
Electrowinning	Solution of nitric acid and silver nitrate; 1–1,000 ppm/Refined silver	0.103
Electrolysis	Silver anode or slime in nitric acid (87–95 percent silver/Refined silver	0.014–0.016

NA = Not available

[1] Estimates do not include the electricity required prior to refining by electrolysis or electrowinning.

[2] The range of estimates reflects the concentration of silver in solution. Greater amounts of electricity are required to recover silver from solutions with low concentrations of silver and high amounts of impurities.

References for Table 42

Ecomaterials Center (Japan), 2003, Estimation of CO_2 emission and energy consumption in extraction of metals: National Institute for Materials Science, Independent Administrative Institution, last accessed June 7, 2011, at *http://www.nims.go.jp/imel/mde-report/Report/01-e-p.pdf.*

Ewart, Ian, and Treasure, Tony, 2011, Electrometals Technologies Limited, Silver electrowinning in the EMEW cell: Electrometals Technologies Limited, last accessed June 6, 2011, at *http://www.electrometals.com.au/technical-reference-papers.html.*

Gekko Systems, 2007, Max Au current efficiency in an electrowinning cell: Gekkos, last accessed June 6, 2011, at *http://www.gekkos.com/forum/viewtopic.php?t=58&start=0&postdays=0&postorder=asc&highlight=&sid=319aa8aa1a9dedd5a8b02e4461523075.*

Rajput, R.K., 2006, Utilisation of electrical power: New Delhi, India, Laxmi Publication Ltd., 709 p., last accessed February 3, 2011, at *http://books.google.com/books?id=6z0wRsbPxI4C&pg=PA152&lpg=PA152&dq=kwh+nicken+refining&source=bl&ots=UazObM9a7x&sig=UtMqEY42S2nw6DiXIU21NOsbaxM&hl=ee&ei=Fg1KTeLLJ4j4swPRotjhCg&sa=X&oi=book_result&ct=result&resnum=1&sqi=2&vev=0CBMQ6AEwAA#v=onepage&q=kwh%20nickel%20refining&f=false.*

Tan Khay, G.J., and Dinardo, Orlando, 1991, Hydrometallurgical silver refining: Discover Intellectual Property, last accessed August 8, 2011, at *http://ip.com/patapp/CA2017032A1.*

Table 43. Estimated electricity requirements for the production of titanium and selected titanium-containing products.

[kWh/t, kilowatt hours per metric ton]

Product and process	Feedstock	Specific electricity usage (kWh/t product[1])
	Synthetic rutile	
Becher process	Ilmenite concentrate	300–350[2]
	Titanium sponge	
Kroll process	$TiCl_4$ from ilmenite or rutile	22,000–37,000 w/o vacuum distillation[3,4]
	Pure titanium sponge	
Vacuum distillation	Impure titanium sponge	15,000[4]
	Titanium pigment	
Chlorination process	High-grade rutile, synthetic rutile, and/or slag	650–1,800[2]
Sulfate process	Ilmenite or slag	1,100–2,500[2]
	Titanium slag[5]	
Electrosmelting	Ilmenite	2,100
	Titanium metal[6]	
Double-arc melting	Titanium sponge	4,500–5,500
Vacuum arc remelting (VAR)	Titanium sponge	3,000

[1] In some cases, it was difficult to discern between estimates for energy requirements, which may include fossil fuels and electricity requirements. Electricity requirements can vary because of ore grades, operating conditions, economies of scale, and numerous other factors that affect the production process. Electricity requirements for ancillaries associated with the facilities were not estimated, but because of the high electricity intensity associated with titanium products an additional burden of less than 15 percent could be expected.

[2] Using the chloride process to produce titanium pigment from different materials was estimated at 1,300 kWh/t for ilmenite, 888 kWh/t for Richard's Bay slag, and 750 kWh/t for rutile. If produced on site, approximately 53 kWh is required to produce a ton of chlorine. Sulfuric acid production requires approximately 18 kWh/t of acid. The treatment of effluents from a plant with ilmenite as a feedstock and using the sulfate process was estimated at 600 kWh/t of pigment produced, and using titanium slag as a feedstock, 200 kWh/t of pigment.

[3] The electricity requirement for producing sponge using the Kroll process is approximately 37,000 kWh/t of sponge and includes magnesium production, which is 97 percent of the total energy requirement. Estimates for producing pigment from the chloride and sulfate process are 1,800 and 2,500 kWh/t of pigment, respectively. Vacuum distillation is a widely used method of upgrading titanium sponge and has generally replaced the acid-leaching method.

[4] The Hunter process consumes roughly the same amount of electricity per ton of product as the Kroll process. It is unclear if chlorine and magnesium recycling is included in the estimates for the Kroll process.

[5] Titanium slag is used to produce pigments, titanium metal, welding fluxes, and other specialized products.

[6] High-quality titanium metal is produced from the melting of pure titanium sponge.

References for Table 43

AcTed Consultants, 1997, Rutile and ilmenite—Australia's production and potential profile: Chemlink, last accessed September 20, 2010, at *http://www.chemlink.com.au/titan_rutile.htm.*

AcTed Consultants, 1997, Titanium dioxide pigment (and titanium metal): Chemlink, last accessed September 20, 2010, at *http://www.chemlink.com.au/titanium.htm.*

Francois, Cardarelli, 2003, A method for electrowinning of titanium metal or alloy from titanium oxide containing compound in the liquid state: World Intellectual Property Organization, International Publication Number WO 03/046258 A2, last accessed August 9, 2011 at *http://www.francoiscardarelli.ca/PDF_Files/Patent_WO_2003_046258_A3.pdf.*

Kirk, Othmer, 2007, Titanium and titanium alloys, *in* Othmer, Kirk (ed.), Encyclopedia of chemical technology (5th ed.), v. 24: Hoboken, NJ, John Wiley & Sons, 998 p., also available at *http://webcache.googleusercontent.com/search?q=cache:J_frPEqlDO0J:www.scribd.com/dod/30132127/Titanium-and-Titanium-*.

Marsh, Elizabeth, 1996, A technological and market study on the future prospects for titanium to the year 2000: European Commission Joint Research Centre, last accessed September 20, 2010, at *http://www.p2pays.org/ref/05/04159.pdf.*

Murty, C.V., Upadhyay, R., and Asokan, S., 2007, Electrosmelting of ilmenite for the production of TiO_2 slag—Potential of India as a global player: Pyrometallurgy, last accessed September 20, 2010, at *http://www.pyrometallurgy.co.za/InfaconXI/078.pdf.*

National Materials Advisory Board, 1982, Considerations in choice of form for the National Stockpile: Washington, D.C., National Academy Press, Publication NMAB-378, last accessed August 12, 2010, at *http://books.google.com/books?id=oy4rAAAAYAAJ&pg=PA104&lpg=PA104&dq=synthetic+rutile+kwh&source=bl&ots=5QUUiBFjh6&sig=IJARB22NDCuNtgsrMGtzdhm-2r4&hl=en&ei=b7t2TOTcN4fGsAOz-JigDQ&sa=X&oi=book_result&ct=result&resnum=8&ved=0CC4Q6AEwBw#v=onepage&q=synthetic%20rutile%20kwh&f=false.*

National Materials Advisory Board, 1983, Titanium—Past, present, and future: Washington, D.C., National Academy Press, Publication NMAB-392, last accessed August 14, 2010, at *http://books.google.com/books?id=MkErAAAAYAAJ&pg=PA50&dq=energy+titanium+sponsp+electricity&hl=en&ei=gqR9TPssjdCwA5v7oYMH&sa=X&oi=book_result&ct=result&reresn=1&ved=0CDIQ6AEwAA#v=onepage&q=energy%20titanium%20sponge%20electricite&f=false.*

Pistorius, P.C., and Coetzee, C., 2002, Physiochemical aspects of titanium slag production and solidification: Metallurgical and Materials Transactions B, v. 34, no. 5, p. 581–588, also available at *http://www.springerlink.com/content/e264u5g369831719/.*

Roskill Information Services Ltd., 1991, The economics of titanium (7th ed.): London, England, Roskill Information Services Ltd.

Tyler, R.M., and Minnitt, R.C., 2004, A review of sub-Saharan heavy mineral sand deposits— Implications for new projects in southern Africa: Journal of the South African Institute of Mining and Metallurgy, March 2004, p. 89–94, last accessed August 9, 2010, at *http://www.saimm.co.za/Journal/v104n02p089.pdf.*

Table 44. Generalized electricity requirements for the production of yellowcake (U_3O_8).

[kWh/t, kilowatt hours per metric ton]

Generalized process description	Feedstock/product	Estimated electricity usage (kWh/t U_3O_8[1])
Conventional (crush, grind, leach, and precipitate)	Uranium ore (feed grade @ 0.03 percent U_3O_8)/yellowcake	48,000
Conventional (crush, grind, leach, and precipitate)	Uranium ore (feed grade@ 0.05 percent U_3O_8)/yellowcake	31,000
Conventional (crush, grind, leach, and precipitate)	Uranium ore (feed grade@ 0.09 percent U_3O_8)/yellowcake	19,000
Conventional (scrub, cyclone, screen, thicken, leach, and precipitate)	Uranium ore (feed grade@ 0.05 percent U_3O_8)/yellowcake	44,000
Uranium bearing leachate derived from in-situ leaching followed by elution, precipitation, drying, and packaging	Uranium leachate (feed grade average approximately 65 ppm [0.007 percent U_3O_8]/yellowcake)	100,000–130,000

[1] The estimates of electricity requirements are based on data provided in several feasibility studies and are considered to be general estimates for recovering yellowcake (U_3O_8) from conventional mining and in-situ leaching of ore. The amount of electricity required to recover yellowcake as a primary commodity may vary significantly from site to site based on numerous factors. The major factors affecting electricity use include mine type (surface, underground, or in-situ leach), ore feed grade and the chemical and physical nature of the ore, overall recovery, types of technologies used to recover yellowcake, and treatment of waste.

References for Table 44

Graves, Douglass, and Yovich, Matthew, 2008, Preliminary assessment—Nichols Ranch Uranium In-Situ Recovery Project—Powder River Basin, Wyoming, U.S.A.: Uranerz Energy Corporation, Technical Report NI 43-101, last accessed August 11, 2010, at *http://www.uranerz.com/i/pdf/TR-PA-Nichols-Ranch-ISR-SEDAR.pdf.*

Mantra Resources Limited, 2010, Mantra's pre-feasibility study lifts annual production by 48 percent and confirms project economics for the Nyota prospect: Mantra Resources, last accessed August 14, 2010, at *http://mantraresources.com.au/upload/documents/releases/asx/20100301_100301-PFS_Final.pdf.*

Mayfield-Aker Kvaerner, 2006, Honeymoon Uranium Project—Summary of feasibility study: Uranium One, last accessed September 4, 2010, at *http://www.uranium1.com/uploads/filing/Honeymoon%20Technical%20REport.pdf.*

Mega Uranium Ltd, 2009, Lake Maitland—Preliminary assessment and project status November 2009: Mega Uranium Ltd., National Instrument 43-101 Technical Report, 296 p., last accessed August 14, 2010, at *http://www.megauranium.com/UserFiles/Mega-43-101-technical-report.pdf.*

SRK Consulting, 2010, NI 43-101 preliminary assessment: Weld County, Colorado, Powertech Uranium Corp., 162 p., last accessed August 11, 2010, at *http://www.powertechexposed.com/2010.08.%20NI%2043-101%20Preliminary%20Assessment.pdf.*

Table 45. Estimated electricity requirements for the production of vanadium oxide (vanadium pentoxide) from pig iron.

[kWh/t, kilowatt hours per metric ton]

Product	Electricity usage[2,3] (kWh/t product[1])	Specification[1]
Vanadium oxide (vanadium pentoxide)[1]	3,000	Content greater than 99 percent V_2O_5

[1] Product specifications may vary. Specification data may be incomplete. Vanadium oxide produced from magnetite ore is produced from molten pig iron as a product of the iron and steel-making process. Molten pig iron (containing 1.25 percent vanadium) is oxygen-blown to produce a vanadium pentoxide slag containing 12–24 percent vanadium pentoxide and further processed to various purities of vanadium pentoxide using a roast-leach process.

[2] The initial process employed to produce vanadium oxide at the Evraz Highveld plant is not an energy intensive burden on vanadium oxide production because most of the initial energy is expended in the production of iron and steel derived from ores at the Mapochs magnetite mine near Roossenekal, South Africa. Electricity consumption estimates per t of vanadium oxide are approximations based on limited data addressing the blowing of pig iron to produce vanadium pentoxide products.

[3] Includes crushing, grinding, and one or more of the following: roast-leach, rotary-kiln, electric-smelting, shaking-ladle, and basic-oxygen-furnace operations.

References for Table 45

EVRAZ Highveld Steel and Vanadium, 2010, Company website: EVRAZ Highveld, last accessed August 14, 2010, at *http://www.evrazhighveld.co.za/general.asp.*

Morrell, S., 2009, Predicting the overall specific energy requirements of crushing, high pressure grinding roll, and tumbling circuits: Minerals Engineering, v. 22, p. 544–549, last accessed August 14, 2010, at *http://www.jktech.com.au/Products_Services/Laboratory-Services/Comminution-Testing/SMC-Test/PredictingNOV09.pdf.*

Table 46. Estimated electricity requirements for the production of zinc and lead metal.
[kWh/t, kilowatt hours per metric ton]

Process	Feedstock	Electricity usage [kWh/t ore (o), concentrate (c), sinter (s), zinc metal (Zn), lead metal (Pb)][1]
	Zinc - Electrolytic Process[2]	
Concentrate production	Ore	31 (o)
Roasting, leaching, and acid production	Concentrate	800 (Zn)
Electrolytic refining	Zinc solution	3,000–3,500 (Zn)
	Bulk Pb-Zn - Imperial Smelting[3]	
Concentrate production	Ore	31 (o)
Sintering[4]	Concentrate	335 (c)
Imperial smelting sinter[5]	Concentrate	455 (Zn)
Imperial smelting sinter[6]	Concentrate	114 (Pb)
Imperial smelting sinter[6]	Concentrate	174 (Zn)
Refining of lead	Crude lead	3 (Pb)
Refining of zinc	Crude zinc	25 (Zn)
	Lead – Blast furnace[7]	
Concentrate production	Ore	31 (o), 265 (Pb)
Sintering[4]	Concentrate	335 (c), 590 (Pb)
Furnace	Sinter	95 (s), 160 (Pb)
Pyro-refining	Crude lead	3 (Pb)
Electro-refining[8]	Crude lead	120–165 (Pb)

[1] The amount of energy required to produce metal from each of the three processes can vary considerably owing to such factors as ore and concentrate grades, plant recoveries, and operating efficiency.

[2] The ore grade for the electrolysis (electrorefining) model was 8.6 percent Zn, 5.5 percent Pb, and 20 percent S. The zinc concentrate grade was 50.3 percent Zn, 3.1 percent Pb, and 29.8 percent S. Rajput (2006) estimates a range of 3,000 to 5,000 kWh/t of zinc metal recovered using the electrorefining process. The electrolytic zinc process is used for approximately 90 percent of the world's primary zinc production from concentrate.

[3] The feedstock for the Imperial Smelting process was based on a concentrate containing 35.3 percent Zn, 21.6 percent Pb, and 26.1 percent S. The Imperial Smelting process is a bulk processing method heavily dependent on fossil fuels as a source of energy.

[4.] Includes 270 kWh/t of concentrate for sulfuric acid production.

[5] The total electricity requirement for a bulk concentrate burdened on KWh/t of recovered zinc.

[6] Electricity consumption allocated by commodity and includes a proportional share of acid production.

[7] The blast furnace model was based on a feedstock consisting of a lead concentrate containing 57.9 percent Pb, 6.1 percent Zn, and 18.8 percent S. Most primary lead is produced using this technology.

[8] Eletro-refining of lead by electrolysis is practiced on low-grade, high-impurity lead.

References for Table 46

Ecomaterials Center (Japan), 2003, Estimation of CO_2 emission and energy consumption in extraction of metals: National Institute for Materials Science, Independent Administrative Institution, last accessed June 7, 2011, at *http://www.nims.go.jp/imel/mde-report/Report/01-e-p.pdf.*

Fugleberg, Sigmund, 1999*,* Finnish expert report on best available techniques on zinc production: Finnish Environmental Institute, last accessed June 14, 2011, at *http://www.ymparisto.fi/download.asp?contentid=10726&lan=en.*

Ifri Energy Program, 2002, Implications of the EU ETS on the zinc sector: Ifri Energy Program, last accessed September 4, 2010, at *http://www.ifri.org/files/Energie/meynckens.pdf.*

Norgate, T.E., and Rankin, W.J., 2002, An environmental assessment of lead and zinc production processes, *in* International Conference on the Sustainable Processing of Minerals, Cairns, Queensland, May 2002: Cairns, Queensland, International Conference on the Sustainable Processing of Minerals, p. 177–184, last accessed September 4, 2010, at *http://www.minerals.csiro.au/sd/CSIRO_Paper_LCA_PbZn.pdf.*

Prada, F.T., and Asselin, E., 2009, Reducing power consumption in zinc electrowinning: CBS Business Network, last accessed May20, 2011, at *http://findarticles.com/p/articles/mi_qa5348/is_200910/ai_n42043138/.*

Rajput, R.K., 2006, Utilisation of electrical power: New Delhi, India, Laxmi Publications Ltd., 709 p., last accessed February 3, 2011, at *http://books.google.com/books?id=6z0wRsbPxI4C&pg=PA152&lpg=PA152&dq=kwh+nicken+refining&source=bl&ots=UazObM9a7x&sig=UtMqEY42S2nw6DiXIU21NOsbaxM&hl=ee&ei=Fg1KTeLLJ4j4swPRotjhCg&sa=X&oi=book_result&ct=result&resnum=1&sqi=2&vev=0CBMQ6AEwAA#v=onepage&q=kwh%20nickel%20refining&f=false.*

Rosenqvist, Terkel, 2004, Principles of extractive metallurgy (2nd ed.): Trondheim, Norway, Tapir Academic Press, 506 p.

Thibault & Associates Inc., 2010, Mount Pleasant Zone—Preliminary assessment: Ontario, Canada, Adex Mining, Technical Report NI 43-101, last accessed May 20, 2011, at *http://www.adexmining.com/financial/pdf/Adex%2043-101%20Technical%20Report%20for%20NZ%20Jan.%2025,%202010.pdf.*

Weisong, Xiao, Bin, Xu, Zhiwen, Li, and Qinsheng, Zhao, 2010, High purity electrolytic lead from low grade crude lead, *in* The Second International Congress—Non-ferrous Metals—Part II—Processes of lead-zinc ore and processing methods, Krasnoyarsk, Russia, September 2–4, 2010, Proceedings: Krasnoyarsk, Russia, The Second International Congress—Non-ferrous Metals—Part II—Processes of lead-zinc ore and processing methods, p. 71–78, last accessed May 24, 2011, at *http://www.nfmsib.com/media/pdf/2010/part2.pdf.*

For more information concerning this publication, contact:
Director, USGS National Minerals Information Center
988 National Center
Reston, VA 20192
(703) 648-6140

Or visit the National Minerals Information Center Web site at:
http://minerals.usgs.gov/minerals/