Update of Platinum Production and Addition of Platinum-Group Metals (PGMs) to GREET® 2021

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This technical memo describes updates to the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET®) model regarding the production of the platinum-group metals (PGMs). The energy and water consumption of PGM production is updated from 2014 values that were provided in an Argonne report by Benavides et al. (2015) to new data representing the average energy and water consumption from 2015 to 2019. In addition, the existing "Platinum" module in the GREET2 model is expanded to a "PGM" module in which energy consumption is calculated for four different PGM products (platinum, palladium, rhodium, and gold) with an option to select a mass or market value allocation method. The electricity generation mix for South Africa that is currently in GREET is also updated from data reported by the International Energy Agency (IEA) in 2012 to data reported by the IEA in 2019.

1. Introduction

The GREET2 2020 model contains a module to characterize the material and energy consumption associated with the production of platinum. This module was created in 2015 (Benavides et al. 2015), and all data is sourced from a 2014 report by the Anglo American Platinum mining company. This company's mining and processing facilities are in South Africa, which produces about 70% of the world's supply of PGMs (Benavides et al. 2015). Anglo American Platinum reports data based on the total annual production of their major products: 3 of the PGMs (palladium, platinum, rhodium), as well as gold, nickel, and copper. Gold is frequently associated with and analyzed alongside of the PGMs, so hereafter any reference to the PGMs in this report includes gold. Two additional PGMs, ruthenium and iridium, are considered minor products and are reported by Anglo American Platinum as "other PGMs," while production of the 6th member of the PGMs, osmium, is not discussed by Anglo American Platinum because only trace amounts are produced from PGM ore (Anglo American Platinum 2019a). The “Platinum” module in GREET uses mass or market value allocation to determine the energy consumption for platinum production as a fraction of the total purchased energy that is reported by Anglo American Platinum. New data regarding PGM production by Anglo American Platinum from 2015 to 2019 is now available, and since 2014 we observe changes in the total energy consumption, electricity consumption, fossil fuel consumption, the masses of products produced annually, the market values of the products, and the electricity mix of South Africa that compel an update of the current data in GREET. Furthermore, since energy consumption for platinum is calculated as a share of the total purchased energy for the production of all Anglo American Platinum products, we can easily use the same allocation approach to determine energy consumption for the other PGMs and expand the “Platinum” module to a “PGM” module. The PGMs are commonly used for high-temperature industrial applications, particularly in fuel-related catalysis, so their inclusion in GREET will be beneficial to many LCA studies.

2. Supply Chain for the Production of PGMs

Benavides et al. (2015) report that Anglo American Platinum’s process for PGM production, as shown in Figure 1, consists of four primary stages: mining, concentrating, smelting, and refining. Crude ore containing a mix of metals and metal compounds is first mined using conventional underground or open cut techniques. After being crushed and milled into small particles, the ore then undergoes the concentration stage in which flotation is used to separate waste from the valuable minerals, producing a concentrate with a much higher metal content than the mined ore. This concentrate is dried and smelted in an electric furnace at high temperatures to produce a matte primarily containing the PGMs, nickel, copper, and iron sulfides. After removal of iron and sulfur using oxygen-enriched air, a variety of chemical methods are used to separate and refine the individual metals. The refining process typically involves an initial magnetic separation of nickel and copper from the PGMs followed by techniques such as solvent extraction, distillation, and ion-exchange that separate the PGMs from each other (Benavides et al. 2015). Seymour and O’Farrelly (2012) report the same standard procedure of mining, concentrating, smelting, and refining for PGM production from crude ore, and they provide additional details regarding the specific chemical reactions required for the purification of each metal.

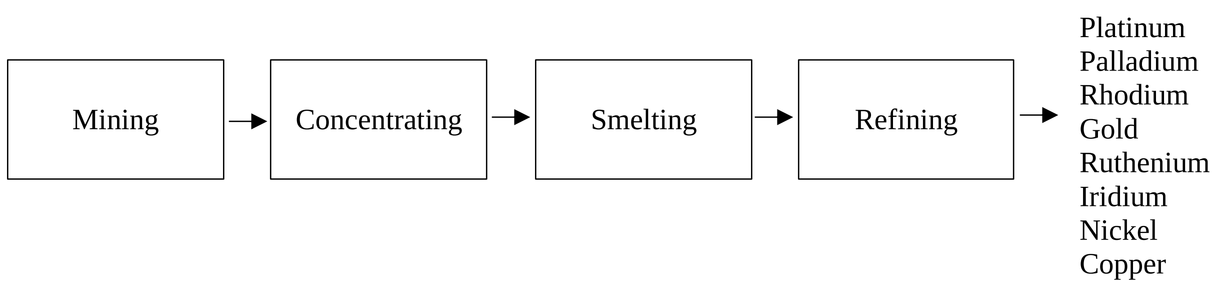

Figure 1. Supply chain for the production of PGMs, nickel, and copper

It is important to note that the PGMs all undergo the mining, concentrating, smelting, and refining processes together, so the individual energy consumption of each PGM may be calculated in the same manner. Anglo American Platinum reports their total purchased energy for the mining, concentrating, smelting, and refining of the PGMs, and energy consumption may then be allocated to each individual product using its production mass or market value. The production of nickel and copper is already well-documented within the GREET2 model, so allocated energy consumption is not calculated for these metals, although we account for their contribution to the total production mass and market value of all products when determining the energy consumption of the PGMs.

3. Update of Purchased Energy and Fuel Shares for PGM Production

Anglo American Platinum's reported purchased energy for PGM production in 2014 and the average from 2015-2019 are displayed in Table 1. For the years 2015-2019, the average value for energy consumed during annual production is 22.28 petajoules (PJ) (Anglo American Platinum 2019b). This value corresponds to all purchased energy involved in the production of the PGMs, nickel, and copper. As shown in Table 1, there is a slight decrease from the value of 22.63 PJ that is reported for total purchased energy in 2014. More specifically, energy from purchased electricity has decreased by 4% while energy from purchased fossil fuels has increased by 4%. Electricity production in South Africa is very intensive in terms of greenhouse gas (GHG) emissions because it is primarily sourced from coal (Benavides et al. 2015). Over the past several years, Anglo American Platinum has implemented several strategies to reduce electricity consumption throughout their production (Anglo American Platinum 2019b). For example, new electrohydraulic rock drills improve energy efficiency during mining, while shock-break technology reduces energy consumption during concentration by using high-speed blades to more efficiently crush and grind crude ore to particle size. New technology is also being incorporated into both smelting and refining equipment in order to generate electricity from waste heat and minimize purchased electricity (Anglo American Platinum 2019b). Although Anglo American Platinum's purchase of fossil fuels has increased slightly, the net effect since 2014 is still an overall reduction in purchased energy since electricity is the primary energy source in PGM production.

Table 1. Change in Anglo American Platinum's purchased energy from 2014 to 2015-2019

Fuel Type	Purchased Energy in 2014 (PJ)	Purchased Energy in 2015-2019 (PJ)	Percent Change
Electricity	16.38	15.78	-4%
Processes and Fossil Fuels	6.26	6.49	+4%
Total	**22.63**	**22.28**	**-2%**

In the "Platinum" module of the GREET2 2020 model, the total purchased, or consumed, energy is presented as a sum of the energy consumption of each process stage (mining, concentrating, smelting, and refining) (Benavides et al., 2015). However, Anglo American Platinum no longer reports this thorough characterization of energy consumption for their 2015-2019 production as they did when reporting the 2014 data. In the 2019 environmental report (Anglo American Platinum 2019b), which provides a five-year review of their annual purchased energy from 2015-2019, one total value is reported for purchased energy across all PGM production process stages. For the new update using this 2015-2019 data, we therefore input energy consumption as a total across all process stages instead of as separate inputs for mining, concentrating, smelting, and refining. Since only the total energy consumption is used in cradle-to-gate calculations, we find this will also simplify the structure of the PGM module.

However, the energy consumption reported by Anglo American Platinum in 2014 was also previously divided by fuel type, describing the contribution of electricity, diesel, coal, and natural gas to the total energy consumption (Benavides et al., 2015). For PGM production from 2015-2019, the contribution of electricity to the total purchased energy is still defined, but the consumption of diesel, coal, and natural gas is reported as a combined total entitled "energy from processes and fossil fuels" (Anglo American Platinum 2019b). Therefore, to obtain the division of fuel types in 2015-2019, we estimate the contribution of each energy input (electricity, diesel, coal and natural gas) based on the 4% variation presented in Table 1. We then calculate the percent contribution of each fuel type to the total energy consumption from 2015-2019 that was reported by Anglo American Platinum (2019b). To verify this approach, we take the sum of the individual fuel type consumption values after propagating the percent changes, and we compare this calculated total to the total energy consumption reported directly by Anglo American Platinum (2019b). We find that when using our estimation for each fuel type, the sum of the consumed energy from all fuel types is 22.26 PJ, which is very near to the value (22.28 PJ) that Anglo American Platinum (2019b) reports for 2015-2019 production. Furthermore, the percent shares of each fuel type for 2015-2019 are very similar to those reported in 2014. The contribution of each fuel type to the total purchased energy for 2015-2019 production is displayed in Table 2.

Table 2. Anglo American Platinum's average annual purchased energy from 2015-2019

Fuel Type	Purchased Energy (PJ)	% of Total
Electricity	15.79	71%
Diesel/petrol	2.55	11%
Coal	3.72	17%
Natural Gas	0.23	1%
Total	**22.28**	–

4. Allocation of Consumed Energy to Individual Products by Mass and Market Value

Either a mass or market value allocation approach may be used to allocate the energy consumption and emission burdens of Anglo American Platinum's total production to each individual product. Mass allocation involves dividing the total energy consumption by the total production mass in order to calculate energy consumed per ton of product. The average 2015-2019 production masses of all products were supplied by Anglo American Platinum (2019a) and are provided in Table A-1 in the Appendix. The results of the mass allocation approach are shown in Table 3 in units of million British thermal units (mmBtu) per ton of PGM. It is important to note that energy consumption by mass allocation is the same for all PGMs since the total production mass of all products is used in the calculation. Since 2014, energy consumption by mass allocation has changed significantly; we find there to be a 19% increase in the total consumed energy per ton of platinum or PGM produced, from 404.2 mmBtu/ton platinum in 2014 to 479.3 mmBtu/ton platinum or PGM over 2015-2019. This is because the total consumed energy of Anglo American Platinum's production has not changed significantly since 2014 (Anglo American Platinum 2019b), while the total production mass has markedly decreased (Anglo American Platinum 2019a), so similar energy is being consumed to obtain less product. Mass allocation is set as the default method in GREET and can be used to determine consumed energy for the production of platinum, palladium, rhodium, gold, ruthenium, or iridium.

Table 3. Average 2015-2019 energy consumed per ton of PGM produced (mass allocation)

Fuel Type	Mass Allocation mmBtu/ton PGM
Electricity	340.1
Diesel	54.8
Coal	80.1
Natural Gas	4.9
Total	**479.9**

The market value method allocates energy consumption based on how much each product contributes to the total monetary value of all products per year. The average 2015-2019 market prices of the products are supplied by Anglo American Platinum (2019a) and are provided in Table A-2 in the Appendix. Energy consumption using this approach varies according to the market price and production mass of each individual PGM. It is important to note that energy consumption for ruthenium and iridium cannot be calculated using market value allocation because the specific production masses of these two metals are not reported, although they are included in the total production mass and may thus be accounted for using mass allocation. For this reason, ruthenium and iridium are excluded from implementation in GREET, and the mass allocation values for platinum, palladium, rhodium, or gold may be used as a surrogate if ruthenium or iridium is needed for a future production pathway. Energy consumption by market value allocation for platinum, palladium, rhodium, and gold is presented in Table 4.

Table 4. Average 2015-2019 energy consumed per ton of PGM produced (market allocation)

	Market Allocation mmBtu/ton PGM			
	Platinum	Palladium	Rhodium	Gold
Electricity	90,122	90,370	166,848	120,385
Diesel	14,531	14,571	26,902	19,411
Coal	21,234	21,292	39,311	28,364
Natural Gas	1,289	1,292	2,386	1,721
Total	**127,175**	**127,525**	**235,447**	**169,881**

5. Notes on Emissions Calculations in GREET2

In order to calculate the emissions associated with PGM production, we model the combustion of each fuel type using the same technology that was selected by Benavides et al. (2015). However, emissions are now calculated using the total consumed energy across all process stages as opposed to performing individual emissions calculations for each process stage. We thus need to account for any differences in combustion technology among the four process stages within our calculations. The mining, concentrating, smelting, and refining stages of PGM production all utilize coal industrial boilers for coal combustion and NG industrial boilers for natural gas combustion, so the emissions associated with the combustion of coal and natural gas are the same for all four process stages. In addition, the type of coal and natural gas consumed during all four stages are the same, so upstream energy consumption and emissions associated with coal and natural gas production are the same. However, the mining process of PGM production consumes low-sulfur (LS) diesel that is combusted in heavy heavy-duty trucks, while the concentrating, smelting, and refining stages all consume conventional diesel that is combusted in stationary reciprocating engines. Mining accounts for 96.3% of the total diesel consumption and combustion, while concentrating, smelting, and refining collectively account for the remaining 3.7% of diesel consumption and combustion. Therefore, when calculating emissions associated with diesel, we use a weighted sum; 96.3% of the total diesel input is multiplied by the emissions factors for LS diesel production and combustion in heavy heavy-duty trucks, while 3.7% of the total diesel input is multiplied by the emissions factors for conventional diesel production and combustion in stationary reciprocating engines. The same approach is used for the upstream energy consumption of LS diesel and conventional diesel production. The combustion technology for each fuel type that is used during PGM production is summarized in Table 5.

Table 5. Combustion technology used for each fuel type in PGM production

Fuel Type	Combustion Technology	Share in Combustion Process
Diesel	Heavy heavy-duty truck[a]	96.3%
	Stationary reciprocating engine[b]	3.7%
Coal	Coal industrial boiler	100%
Natural Gas	NG industrial boiler	100%

[a]LS diesel is combusted in heavy heavy-duty trucks during mining

[b]Conventional diesel is combusted in stationary reciprocating engines during concentrating, smelting, and refining

6. Update of Water Consumption for Anglo American Platinum Production

Anglo American Platinum reports a total value for annual water consumption which may then be divided by the total production mass to determine the water consumption per ton of product (Anglo American Platinum 2019b). The average water consumption from 2015-2019 is shown in Table 6.

Table 6. Average water consumed per ton of PGM produced from 2015-2019

	Gal/ton PGM
Water Consumption	171,176

7. Update of South African Electricity Mix

Electricity production in South Africa is still sourced primarily from coal, but the contribution of coal has decreased from 92.7% in 2012 (Benavides et al. 2015) to 87.6% in 2019 (IEA 2019). Since PGM production consumes energy primarily from purchased electricity, this change could potentially impact the cradle-to-gate fossil fuel consumption for PGM production. The updated electricity mix that we implement into GREET is shown in Table 7. No new data has been reported since 2014 for the electric power transmission and distribution (T&D) losses, so we maintain the value of 8% that is currently in GREET (World Bank 2018).

Table 7. South Africa 2019 electricity grid mix

Electricity Source	% of Total
Petroleum	0.1
Natural gas	0.0
Coal	87.6
Biomass	0.2
Nuclear	5.4
Hydro	2.2
Other	4.5

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APPENDIX

Mass allocation requires the total refined production mass as a calculation input, while market value allocation requires each product's production mass as well as the market values of all products. Anglo American Platinum (2019a) provides a five-year review of both the refined production masses and market values of all products from 2015 to 2019. The average refined production from 2015-2019 is displayed in Table A-1 while average market values from 2015-2019 are shown in Table A-2.

Table A-1. Average 2015-2019 refined production of Anglo American Platinum products

Product	Annual mass production (ton/yr)	% by Mass
Platinum	76.4	0.17
Palladium	49.1	0.11
Rhodium	9.8	0.02
Gold	3.5	0.01
Other PGMs[a]	16.3	0.04
Nickel	27,205	61.8
Copper	16,645	37.8
Total	**44,004**	–

[a]Other PGMs are ruthenium and iridium

Table A-2. Average 2015-2019 market values of Anglo American Platinum products

Product	Annual market value ($/yr)	% by Market Value
Platinum	2,309,358,080	46
Palladium	1,489,453,056	30
Rhodium	546,185,216	11
Gold	140,514,048	3
Other PGMs	157,702,160	3
Nickel	289,608,182	6
Copper	86,175,027	2
Total	**5,018,995,769**	–