

## Article

# PGE Production in Southern Africa, Part II: Environmental Aspects

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**Abstract:** Platinum group elements (PGEs, 6E PGE = Pt + Pd + Rh + Ru + Ir + Au) are used in numerous applications that seek to reduce environmental impacts of mobility and energy generation. Consequently, the future demand for PGEs is predicted to increase. Previous studies indicate that environmental impacts of PGE production change over time emphasizing the need of up-to-date data and assessments. In this context, an analysis of environmental aspects of PGE production is needed to support the environmental assessment of technologies using PGEs, to reveal environmental hotspots within the production chain and to identify optimization potential. Therefore, this paper assesses greenhouse gas (GHG) emissions, cumulative fossil energy demand (CED<sub>fossil</sub>), sulfur dioxide (SO<sub>2</sub>) emissions and water use of primary PGE production in Southern Africa, where most of today's supply originates from. The analysis shows that in 2015, emissions amounted to 45 t CO<sub>2</sub>-eq. and 502 kg SO<sub>2</sub> per kg 6E PGE in the case GHG and SO<sub>2</sub> emissions, respectively. GHG emissions are dominated by emissions from electricity provision contributing more than 90% to the overall GHG emissions. The CED<sub>fossil</sub> amounted to 0.60 TJ per kg 6E PGE. A detailed analysis of the CED<sub>fossil</sub> reveals that electricity provision based on coal power consumes the most fossil energy carriers among all energy forms. Results show that the emissions are directly related to the electricity demand. Thus, the reduction in the electricity demand presents the major lever to reduce the consumption of fossil energy resources and the emission of GHGs and SO<sub>2</sub>. In 2015, the water withdrawal amounted to 0.272 million L per kg 6E PGE. Additionally, 0.402 million L of recycled water were used per kg 6E PGE. All assessed indicators except ore grades and production volumes reveal increasing trends in the period from 2010 to 2015. It can be concluded that difficult market conditions (see part I of this paper series) and increasing environmental impacts present a challenging situation for the Southern African PGE mining industry.

**Keywords:** mining; platinum group metals (PGE); South Africa; Zimbabwe; environmental assessment; greenhouse gas (GHG) emissions; sulfur dioxide emissions; cumulative energy demand (fossil); water demand

## 1. Introduction

Worldwide, PGEs (platinum group elements) are used in a broad range of applications including technologies and sectors aiming for the reduction of environmental impacts (e.g., catalytic converter as an emission control device or as a catalyst in fuel cell driven vehicles). The PGEs are platinum (Pt), palladium (Pd), iridium (Ir), ruthenium (Ru), rhodium (Rh) and osmium (Os). They occur together in nature in combination with minor gold (Au). In the following, the denominations 3E PGE, 4E PGE

and 6E PGE refer to Pt + Pd + Au; Pt + Pd + Rh + Au; and Pt + Pd + Rh + Ru + Ir + Au, respectively. The use of PGEs often symbolizes sustainability-oriented values due to their novelty and potential to reduce environmental impacts. Therefore, the future demand of PGE is predicted to increase due to a rise in these applications. It is therefore essential to understand environmental aspects related to the provision of PGEs.

PGE deposits can only be found in a limited number of sites worldwide. The greatest known deposits of PGEs were discovered in Southern Africa in the Bushveld Complex in South Africa and in the Great Dyke in Zimbabwe (see part I [1]). Thus, the South African and Zimbabwean PGE industries provide most of the today's global PGE demand.

Only very few investigations dealing with environmental impacts of the production of PGEs were published so far. Additionally, there is a substantial lack of detailed inventory data for further, more detailed surveys. The reference works are the studies by Nuss and Eckelman [2] and several publications by Mudd and Glaister [3–6]. These studies address environmental aspects of (PGE) mining using different approaches: Eckelman and Nuss rely on data from the Ecoinvent database [7], which itself is based on data that were published before 2000 [8,9]. The data applied present estimations of relevant parameters for PGE mining and production on a disaggregated level. In contrast, publications of Mudd and Glaister [3–6] present reviews of (aggregated) data published by PGE producers referring to the period from 1995 to 2010. The reference works of Mudd and Glaister indicate an increase in emissions over time [3,6]. This aspect emphasizes the need of the analysis of actual data and the assessment of trends.

In this context, this paper evaluates environmental aspects of PGE production in Southern Africa based on the latest data. Thereby, the results contribute to the existing body of knowledge by providing and up-to-date evaluation of selected environmental aspects. The period from 2010 to 2015 is covered to identify possible changes over time. In a first step, the methodology and data basis for the assessment is explained. Subsequently, a description of the Southern African PGE industry and the process steps required for the production of PGE is given. Thereafter, results are presented for these indicators for the reference year 2015 and for the period from 2010 to 2015 to discuss recent trends based on indicator scores. Furthermore, indicator scores are allocated to individual PGEs to allow the incorporation of results into Life Cycle Assessment (LCA) studies or other assessments that include the environmental performance of a single or multiple PGEs.

## 2. Assessment Methodology and Data Basis

Through a process of literature review, data collection from the mining industry and reflection upon practice the PGE mining in Southern Africa is evaluated in detail for selected environmental aspects (also see part I [1]).

### 2.1. Selection of Environmental Indicators

A selection of indicators is assessed that covers a wide range of environmental aspects that are important in Southern Africa as well as on a global scale:

1. **Energy consumption.** Mining and ore processing is energy-intensive. In recent years, South Africa has faced shortages in energy supply that were alleviated by load shedding programs as demand could not be covered by the electricity supply [10]. Furthermore, energy costs constitute a high share of total production costs [11]. Due to these two aspects, energy consumption is of major interest for PGE producers, energy suppliers and the governments of South Africa and Zimbabwe.
2. **Greenhouse gas (GHG) emissions.** The use of PGEs in the automotive sector is either connected to the reduction of exhaust air pollution by the use of PGEs in catalysts for emission reduction and/or motivated by the aim of reducing GHG emissions and the dependency on fossil fuel resources (e.g., by the use of fuel cell vehicles) (cf. [12–14]). To be able to assess the overall GHG emissions and to gain a complete overview of the life cycle emissions of novel technologies

such as fuel cell vehicles, emissions originating from the provision and production of its various components need to be known.

3. **Sulfur dioxide emissions.** The production of PGEs leads to gaseous and particulate matter emissions from mining and ore processing with a local impact on humans and the natural environment. One of the most severe air quality issue relates to SO<sub>2</sub> emissions [15].
4. **Water consumption.** In Southern Africa, water is an increasingly scarce resource [16]. Some communities faced severe impacts of local water infrastructure failures during 2015. The mining industry is reliant on water for all operation steps.

## 2.2. Assessment Procedure and Data Basis

The assessment of environmental aspects of PGE production is based on data reported by companies combined with production data, scientific literature and other reports. The chosen approach builds on the methodology applied by Mudd and Glaiser [3–6]: In a first step, the industry structure in Southern Africa was analyzed and production data were compiled (see part I [1]). Based thereon, reported data relevant to the assessed indicators were compiled, analyzed and reviewed. The resulting data were complemented by data obtained from scientific literature and technical reports to gain the most comprehensive picture of selected environmental aspects possible (Table 1). Inferred parameters are derived from data obtained from reports combined with data from scientific literature. They complement indicators based on data reported by companies to allow a more comprehensive image of the respective environmental aspect (see below). Results are presented for the reference year 2015 and for the period from 2010 to 2015. Furthermore, results are presented per input material (ore milled) and output (PGE). For each indicator, the data coverage is reported (Figure S1). The data coverage is defined here as the share of production for which data are available to overall production. To apply results to further studies, indicator scores are apportioned to individual PGEs. Results allocated to individual PGEs based on average prices from 2010 to 2015 are presented in Table S1.

**Table 1.** Indicators and related parameters.

Indicator	Parameters Acquired from Reports	Inferred Parameters
Energy consumption	Electricity demand Consumption of liquid fuels, natural gas and coal	Cumulative fossil energy demand (CED <sub>fossil</sub> )
GHG emissions	CO <sub>2</sub> -eq. emissions <sup>a</sup> for Scope 1, 2 and 3	
Sulfur dioxide emissions	Direct SO <sub>2</sub> emissions	Indirect SO <sub>2</sub> emissions
Water withdrawal and recycling	Water withdrawal and use of recycled water	

<sup>a</sup> Scope 1: direct emissions emitted by activities under control of the company; Scope 2: emissions related to electricity provision by external companies (i.e., Eskom and Zimbabwe Power Company); and Scope 3 emissions: emissions of services and products acquired from third parties, product transportation as well as business travel, etc. Not all companies present Scope 3 emissions or include different aspects.

Data were reviewed from multiple companies operating production facilities and mines. There are four integrated companies that run all facilities required from the extraction of ore to the final production of PGEs: Anglo American Platinum Corporation Ltd. [17], Impala Platinum Holding Ltd. [18], Lonmin plc. [19] and Northam Platinum Ltd. [20]. Of those companies, Anglo American Platinum provides more than half of the total PGE production, whereas Impala Platinum, Lonmin and Northam Platinum account for 24%, 14% and 6% of Southern African production, respectively (Figure 1). Other companies operate facilities along the overall production chain, such as single mines, concentrators or tailing retreatment facilities (e.g., Aberdeen International Inc. [21], African Rainbow Minerals Ltd. [22], Aquarius Platinum Ltd. [23], Atlatsa Resource Corporation [24], Eastern Platinum Ltd. [25], Glencore plc. [26], Sedibelo Platinum Mines Ltd. [27], Royal Bafokeng Holdings Ltd. [28], Sylvania Platinum Ltd. [29] and Tharisa plc. [30]). Data acquired from these

companies were complemented by scientific literature and technical reports. Based on the acquired data, the following applies to the selected indicators:

- **Energy consumption.** For the assessment of the overall energy consumption of PGE production in Southern Africa, electricity demand and the consumption of liquid fuels, natural gas and coal are analyzed. The cumulative fossil energy demand ( $CED_{fossil}$ ) is determined based on the  $CED_{fossil}$  of the different energy carriers (Table S2) and the amount of energy required of each energy type. The analysis furthermore considers different processing stages. Electricity consumption and liquid fuel consumption are reported by all companies, whereas the consumption of other energy carriers is not reported by all companies. To estimate the overall energy consumption including other energy carriers, the analysis is based on data reported by Anglo American Platinum, presenting more than 50% of production in 2015. These data are extrapolated to the entire industry.
- **GHG emissions.** GHG emissions are reported by various companies including CO<sub>2</sub> emissions besides other GHGs according to the Intergovernmental Panel on Climate Change [31]. Emissions are reported in Scopes 1–3.
- **Sulfur dioxide emissions.** PGE producers report direct SO<sub>2</sub> emissions originating from the production process. These emissions are complemented by indirect emissions, representing emissions from electricity generation and liquid fuel combustion. These are interfered from scientific literature and data provided by the South African electricity provider.
- **Water withdrawal and recycling.** The withdrawal of surface and ground water, or any other type of freshwater, is considered. Furthermore, the use of recycled water is analyzed.

### 3. System Description

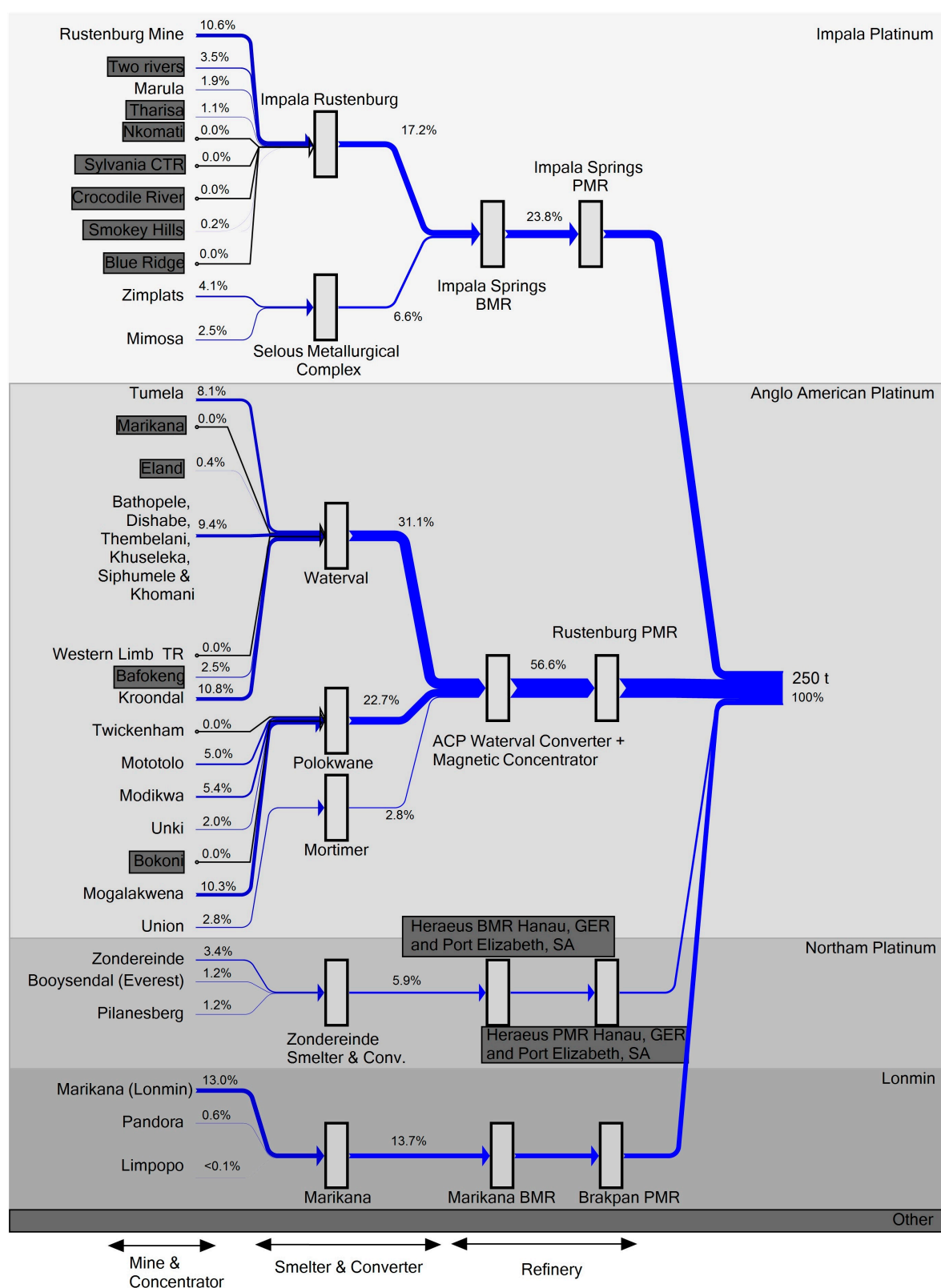
The Southern African PGE mining industry targets mineral deposits in two regions:

- The South African Bushveld Complex measures 450 km by 350 km and it comprises about 63,260 t of the global PGE mineral resources (90,733 t PGEs (4E)) [4]. The main reef types in the Bushveld complex are Merensky reef, UG2 reef and Platereef. These deposits show a concentration of platinum group elements (PGE) ranging from 3 g/t to 10 g/t in ore [32–34]. (A more detailed description of mineral reefs in Southern Africa can be found in part I [1].
- The Great Dyke in Zimbabwe measures about 480 km in length and about 8 km in width and extends in a north to northwest direction [35,36]. It contains two Merensky-type reefs presenting the major source of Pt, Pd and Rh: The Lower and Main Sulfide Zones [33]. At the moment, only the latter is commercially exploited.

The extraction and processing of PGE bearing minerals, involves several steps (Figure 2):

1. Mining;
2. Comminution (e.g., crushing and grinding);
3. Concentration of (e.g., flotation and gravity concentration);
4. Pyrometallurgical concentration (e.g., smelting and converting);
5. Hydrometallurgical extraction of base metals (e.g., leaching and recovery of individual base metals as well as production of a PGE concentrate); and
6. Refining of the PGE concentrate for the production of PGE [37].

At each processing step, the concentration of PGEs increases, while the quantity of material that is processed decreases rapidly from one to another processing step (Figure 3).



**Figure 1.** Industry structure and share of production in 2015. Companies possessing the largest share of an entity are considered as the operator/owner. Data from part I [1].

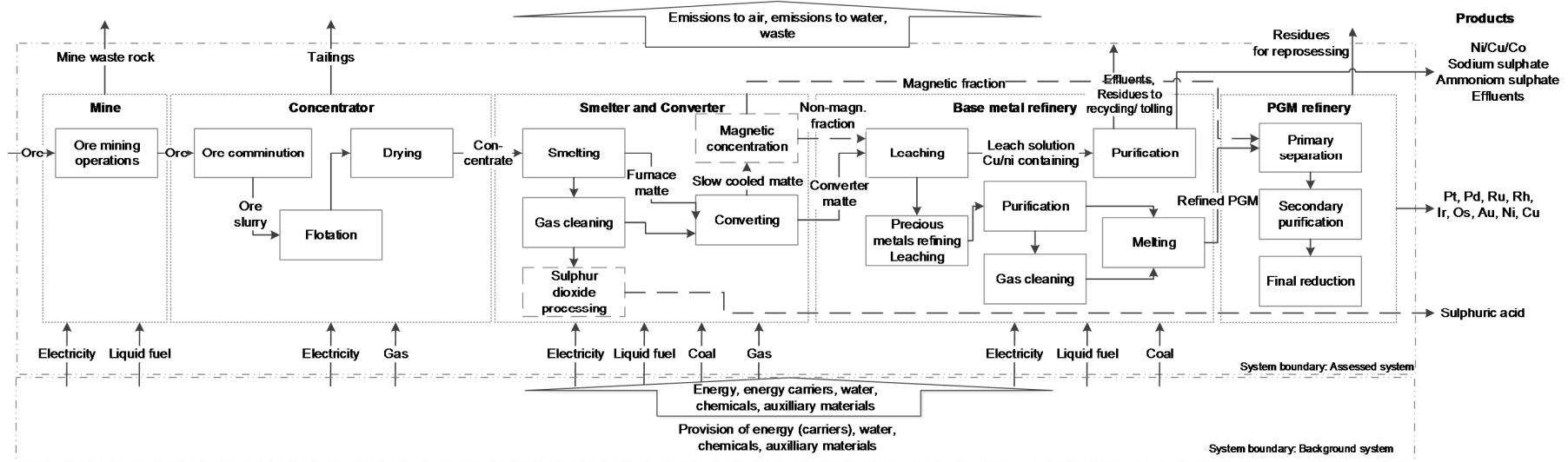


Figure 2. Production steps of PGE production.

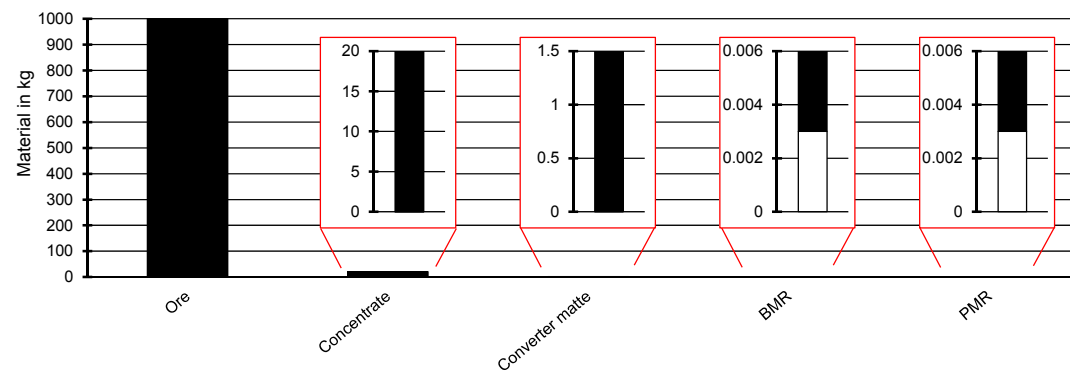


Figure 3. Processed material at each production step, assuming PGE contents of 0.0003%, 0.015%, 0.2%, 50% and 99.95% of ore, concentrate, converter matte, base metal refinery (BMR) leach residue and final precious metal refinery (PMR) product, respectively. Detailed views of each product stream framed in red.



### 3.1. Mining

Mining is typically differentiated between underground mining, i.e., drilling, blasting and hauling of ore from below the surface, and open pit mining. Underground operations are traditionally applied to Merensky-type reefs and UG2-type reef, since these are typically <1 m thick and located deep below the surface [38]. In contrast, open pit methods are used to mine Platreef deposits [39]. Apart from valuable ore, mining hoists large quantities of waste material. The ore to waste ratio is estimated to range 1–5:10 and 6.9–23.7:1 in the case of underground mines and open pit mines, respectively [5]. The mining sector is facing a competitive environment and thus, mining technologies are forced to continuously improve to minimize production costs [40].

The degree of mechanization varies and depends on economic and technical conditions. Thus, the analyzed data contain underground and open pit mining, as well as all degrees of mechanization that are currently used.

### 3.2. Concentrating

Subsequently, the ores are treated to separate the PGEs from ore. Concentration involves the crushing of the ore and the separation of PGE bearing materials. This process step is typically carried out at, or close to, the mine site [33]. Technically, the separation is realized in flotation cells. Reagents are added to increase the PGE content in the slurry about 20 times [39,41]. Two streams are produced: the concentrate, containing 100 g to 400 g PGE (typically in the range of 100 g to 200 g PGE) and waste tailings with about 0.4 g PGE/t (dry basis) [42]. The tailings are discarded to dams, whereas the concentrate is processed in the smelter.

### 3.3. Smelting

Starting with the concentrate, the main process steps are drying and smelting by electric furnaces to a (furnace) matte enriched in PGEs [43]. As ores of the Merensky reefs are different to UG2 reefs, e.g., compared to Merensky ore the UG2 ore has lower contents of nickel and copper sulfides and it contains more chromite, and thus, the ores require different approaches to metallurgical processing [42]. This is dependent on technical specifications and the quantity of UG2 that is processed. Thus, the processing of concentrate from Merensky and UG2 reefs can either be accomplished jointly or separately in different smelters. Smelting is a two-step process:

- In the first step, the concentrate (i.e., slurry) is thickened, filtered and either flash or spray dried until the product contains less than 0.5% water [44,45]. The reduced water content is essential for the next processing step, the electric furnaces, to avoid hydrogen explosions [46].
- In the second step, this material is treated in submerged-arc electric furnaces; for example, in South Africa six of these furnaces are installed in line [42]. The temperature of this smelting process is usually between 1350 and 1600 °C depending on the quality and the composition of the material; for example, for concentrates from UG2, temperatures of around 1600 °C are needed [47].

Apart from molten furnace matte, slag is produced. The ratio of slag to matte is typically 4–9 [43]. The slag is grinded and undergoes froth flotation to separate a phase rich in valuable metals for recycling. Waste slag is discarded. After smelting, the furnace matte is transported to the converter. It is composed of Ni, Cu, Co, Fe, S and the PGEs [42,48]. All furnace mattes are jointly processed in the converter, regardless of the original ore type that was processed.

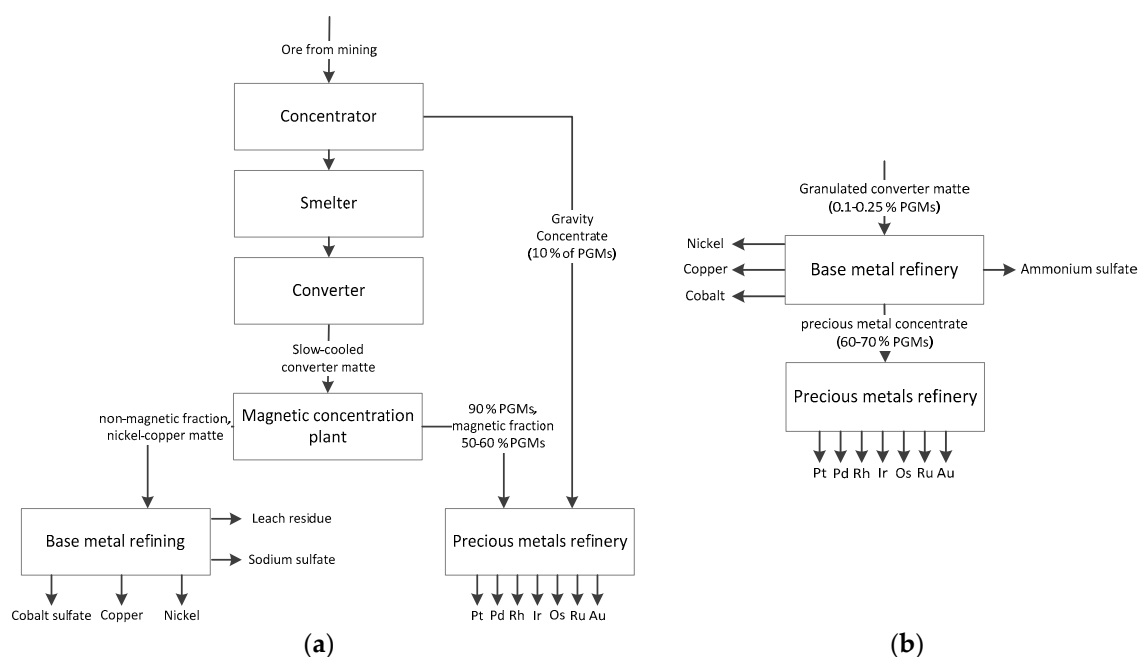
### 3.4. Converter

In this process, a converter matte is produced enriched in PGEs (about 2000 g/t) [46]. In this converting process, sulfur and iron contained in the furnace matte are oxidized to SO<sub>2</sub>, leaving the reactor partially in the vapor phase and slag by blowing air through a top-submerged lance [42].

For a few hours, air is blown into the respective reactor and silica sand is inserted to allow the formation of an iron silicate at temperatures of around 1250 °C. This process yields two products: converter matte and converter slag [42,43,45]:

- The converter matte containing nickel subsulfide, copper(II) sulfide, iron(II) sulfide, small quantities of cobalt and PGEs as well as impurities such as selenium, tellurium, arsenic, lead, tin, antimony, and bismuth) can be processed by
  - a. pouring it into water to granulate; or
  - b. by putting it into cast-iron molds or refractory-lined pits and then crushing it.

In the first case, granulated matte is sent to the base metal refinery. In the second case, matte is cooled down slowly. The slowly cooled matte can be milled and the PGE rich fraction can be separated magnetically. The fraction rich in PGEs is directly sent to the precious metal refinery (PMR), whereas the remaining fraction rich in base metals is further processed in the base metal refinery (BMR) (Figure 4). The converter slag requires further treatment since the conditions in the previous process steps have caused dissolving reactions of valuable base metals (e.g., Co and Ni). Up to 30% of the matte is returned to the furnace to decrease potential losses of PGEs. This also reduces the amount of Cr in the concentrate, with the positive effect, that the load of Cr to the primary smelting furnace is reduced.



**Figure 4.** The magnetic concentration process for separating the PGEs from the base metals (a); and the refining of PGEs from the smelter matte by the whole matte leaching process (b). Adapted from [41].

### 3.5. Base Metal Refining

In the base metal refinery (BMR), the PGEs contained in the matte are separated from the base metals. There are mainly two process routes currently used to separate PGEs depending on the conversion process (Figure 4):

1. **Whole-matte leaching process subsequent to fast cooling.** The process of whole-matte leaching removes Ni and Cu from the converter matte [41]. The PGEs can be gained as an insoluble residue (the PGE content in this residue is about 60%). In the following process steps, the residue is treated to remove residual Cu, Ni, Fe, Se and Te. Subsequently, the residue is transferred to PGE refinery [41].



- 2. Separate refining of base metals and PGEs subsequent to slow cooling.** In the process of slow cooling followed by magnetic separation, the converter matte is cooled slowly for several days to gain relatively large crystals of, e.g., heazlewoodite,  $\text{Ni}_3\text{S}_2$ , chalcocite,  $\text{Cu}_2\text{S}$  and metal alloy [41]. During this process, the PGEs concentrate in the alloy phase. Afterwards they can be separated by magnetic separation (10% of the converter matte is in the form of an alloy). The separated part is then treated in leaching steps to remove Cu, Ni and Fe to upgrade the PGE content. In the following, the PGE-rich fraction is transferred to the PMR. The non-magnetic fraction of the converter matte is transported to the BMR, firstly to leach Cu and Ni into solution and secondly to purify the solutions; i.e., commercial Cu, Ni and Co products are produced.

### 3.6. PGE Refining

The concentrate going into the precious metal refinery (PMR) contains typically between 50% and 70% precious metals and the purity of the product coming out of the refinery is typically greater than 99.9% [33]. Until today, a number of techniques were applied for converting the concentrate coming from the BMR into high quality PGEs. The techniques can be differentiated by primary separation, secondary purification and reduction to metal [33].

The properties and the differences of PGEs in the chemistry of their anionic chloro-complexes (e.g., ligand substitution kinetics, ammonium salt solubility, ion-exchange reactions and redox potentials) are relevant especially for the separation and purification processes [34]. The key aspects of the properties and chemical characteristics are presented in Table 2.

**Table 2.** Key aspects of properties and chemistry of PGEs for the separation processes during PGE refining [34,49].

Parameter	Description
Nobility	In general, PGEs are difficult to be solved in media, whereas almost all of the base metals can be solved in media. The leaching processes of base metals from the PGE-rich sulfide ores make use of this property of PGEs. It can be distinguished between: (i) insoluble PGEs (i.e., Ir, Ru, Rh, Os); and (ii) Pt and Pd dissolving more slowly compared to the former. Under well-defined conditions, a separation between these groups is conceivable.
Chloro-complexes	PGEs form complexes with different ligands. The most relevant complexes are PGE chloro-complexes (obtained with an aqueous chloride solution) since aqueous chloride solution is the most economically feasible option to bring PGEs into solution and thus into concentration.
Ligand substitution reactions	The reactivity of the PGEs varies depending on: (i) the oxidation state of the metal; and (ii) the nature of the reactant ligands.
Volatile tetroxides	Ru and Os can be separated from the other PGEs via distillation due to the fact that under oxidizing conditions Ru and Os form volatile tetroxides.
Ion-exchange reactions	PGE chloro-complexes are formed in acidic chloride media and show mostly anionic characteristics. Hence, PGE chloro-complexes can undergo anion-exchange reactions with salts (i.e., of organic bases). Based on the relative strengths of electrostatic interaction, PGEs were detached with anion exchange resins.
Oxidation states	The equilibrium redox potentials (e.g., for PGE in chloride media) influenced by both kinetic and thermodynamic factors defines the relative concentration of the species in solution at a given potential. The rate of the reduction varies depending on the PGE involved and, hence, by selective oxidation or reduction separation can be achieved.

Several process techniques are currently used for separation, purification and metal reduction, such as dissolution, crystallization and precipitation, hydrolysis, distillation, organic precipitation, solvent extraction, ion exchange and metal reduction [50].

The refining of the PGEs to produce pure metals is highly confidential. In Southern Africa, the three major PGE operators Anglo American Platinum, Impala Platinum and Lonmin each have their own individual PGE refining process (Table 3). These technologies can be characterized as follows [34,49–52]:

1. Precipitation. It is basically the formation of a solid from a solution.
2. Solvent extraction. For the separation of noble metals from their multicomponent mixtures or from the associated base metals, solvent extraction is broadly used. It typically comprises three steps:
  - a. An extraction step from aqueous solutions to extract a specific metal, i.e., neutral solvating agents (e.g., oxygen containing solvents, organo-phosphorous and neutral sulfur containing compounds) or in the form of ion-pairs (e.g., with high molecular weight amines).
  - b. A scrubbing step to remove co-extracted metals.
  - c. A stripping step to gain the extracted metal from the organic phase.
3. Ion exchange. Chromatographic methods are applied for ion exchange to separate noble metals from associated base metals. Cation and anion exchangers can be employed in separation procedures.

#### 4. Results

At first, results for the different indicators are presented for the reference year of 2015 and for the period from 2010 to 2015 to identify possible trends in indicator scores. Results, allocated to individual PGEs, are provided in Table S1. The data coverage of all indicators is presented in Figure S1.

##### 4.1. Energy Consumption

**Electricity demand.** In 2015, the total electricity consumption of PGE production in Southern Africa amounted to 44.9 PJ (Figure 5). The share of electricity demand of each company roughly reflects the market share in 2015 (Figure 1). This corresponds to 0.55 and 0.15 TJ per 1000 t ore milled or kg 6E PGE, respectively. In the period from 2010 to 2015, electricity consumption has fluctuated in absolute terms between 38.5 and 45.1 PJ. An increasing trend can be observed regarding energy consumption per t ore processed: the energy consumption per 1000 t ore milled has increased by 21% from 0.46 TJ in 2010 to 0.55 TJ in 2015. The energy demand per kg 6E PGE of mines, concentrators and smelters increases with decreasing head grades (Figure 6). Data either describe mines and concentrators or mines, concentrators and smelters. In the case of the latter, concentrate from the former is processed. The mine depth and the energy demand show the strongest correlation among analyzed mine parameters (Figures S2–S7). Figure S5 reveals that no clear picture can be drawn regarding the dependency of energy consumption on the share of UG2 that is processed (as previously indicated in Section 3). This is because reported values for mines, concentrators and smelters refer to facilities with a smelter complex that also processes material from other mines, which deliver to the respective smelter.

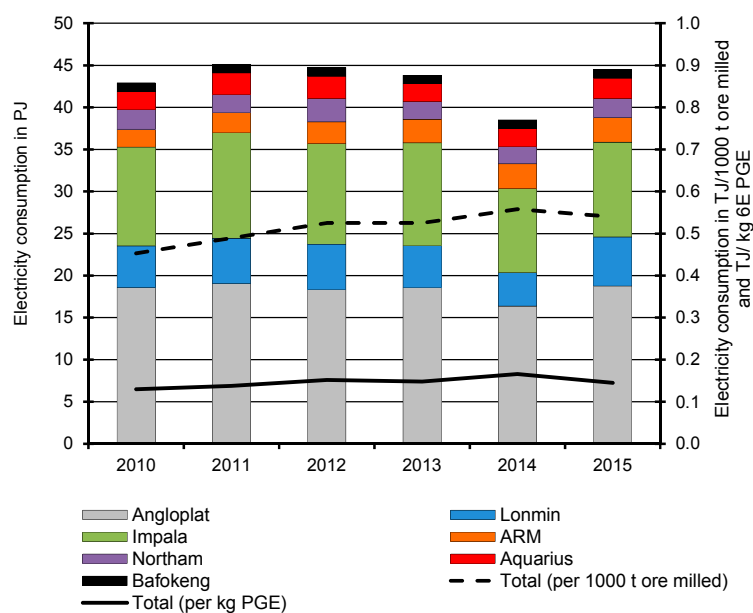
Among all processing stages, mining requires the highest amount of energy (34% of total), followed by smelting (28%), concentration (26%) and refining (12%) (Figure 7a). Among all sources of energy, electricity amounts by far to the largest share (75%). Smelting mainly requires energy for furnaces and flash dryers. The latter are used to dry concentrate before the smelting process. The heat that is required is provided by coal accounting for 7% of the total energy consumption. In the case of mining, electricity accounts for the largest share of energy demand. Large amounts of electricity are required for air compression, ventilation, winders, fridge plants and the operation of pumps.

**Liquid fuels.** In 2015, the PGE industry consumed 157 million L liquid fuels, primarily diesel, but also petrol and other fuels. Similar to electricity demand, liquid fuel consumption increased in recent years: an increase from 2156 to 2470 L/1000 t ore milled in 2010 and 2015, respectively, can be

observed. Diesel fuel is primarily applied for hauling and other transportation needs. It is needed to mine deeper and, thus, increasing amounts of liquid fuels are needed, e.g., for longer haul roads.

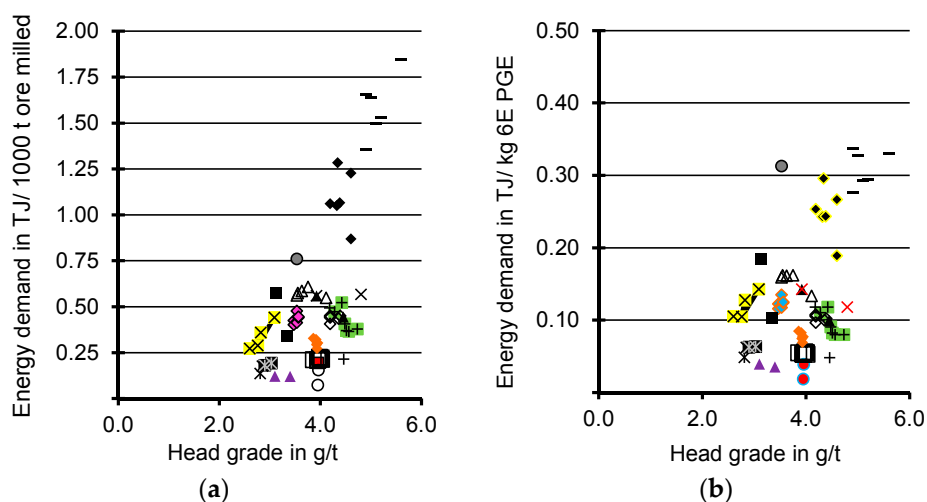
**Table 3.** Methods of PGE extraction in selected refineries [50,53].

Refinery Characteristics	Lonmin	Anglo American Platinum	Impala
Capacity kg	32,000	112,000	71,000
oz	1 million	3.5 million	2.2 million
Technology	Precipitation	Solvent extraction	Ion exchange
Feed quality	65%–75% PGEs	30%–50% PGEs	60%–65% PGEs
Dissolution	HCl/Cl <sub>2</sub> at 65 °C	HCl/Cl <sub>2</sub> at 120 °C	HCl/Cl <sub>2</sub> at 85 °C
Extraction order	Au→Ru→Pt→Pd	Au→Pd→Pt→Ru	Au→Pd→Ru→Pt
<b>Extraction steps</b>			
Au	Crude sponge produced by hydrazine reduction. Secondary processing required.	Solvent extraction, reduction with oxalic acid. No reprocessing.	Ion exchange, reduction with hydroquinone. No reprocessing.
Pd	Precipitation with ammonium acetate. Secondary refining required.	Solvent extraction with b-hydroxyl oxime, stripping with ammonium hydroxide. Minimal reprocessing.	Ion exchange, stripping with ammonium bi-sulfate and precipitation with ammonium hydroxide. Minimal reprocessing.
Pt	Precipitation with ammonium chloride. Secondary reprocessing required.	Solvent extraction with a tertiary amine, tri-n-octylamine, stripped with HCl, and precipitated with ammonium chloride.	Precipitation with ammonium chloride.
Ru	Distillation with sodium chlorate and bromate.	Distillation with sodium chlorate and bromate.	Distillation with sodium chlorate and bromate.
Ir	Precipitation with ammonium chloride.	Solvent extraction with secondary amine organic, n-iso-tridecyl tri-decanamide.	Ion exchange, precipitation with ammonium chloride.
Rh	Precipitation as Claus salt, Rh(NH <sub>3</sub> ) <sub>5</sub> Cl <sub>3</sub> , purification, precipitation with ammonium chloride.	Ion-exchange, followed by precipitation with diethylene tri-amine.	Precipitation with an organic ammine.
<b>First-pass yields (%) / Typical Recoveries (%)</b>			
Pt	86/99	94/99.5	95/99.5
Pd	90/98	92/97.5	95/99.5
Au	92/99	84/99.5	98/94
Rh	77/93	82/99.5	82/98
Ru	86/98	90/99.5	82/99
Ir	70/90	-/99.5	66/94

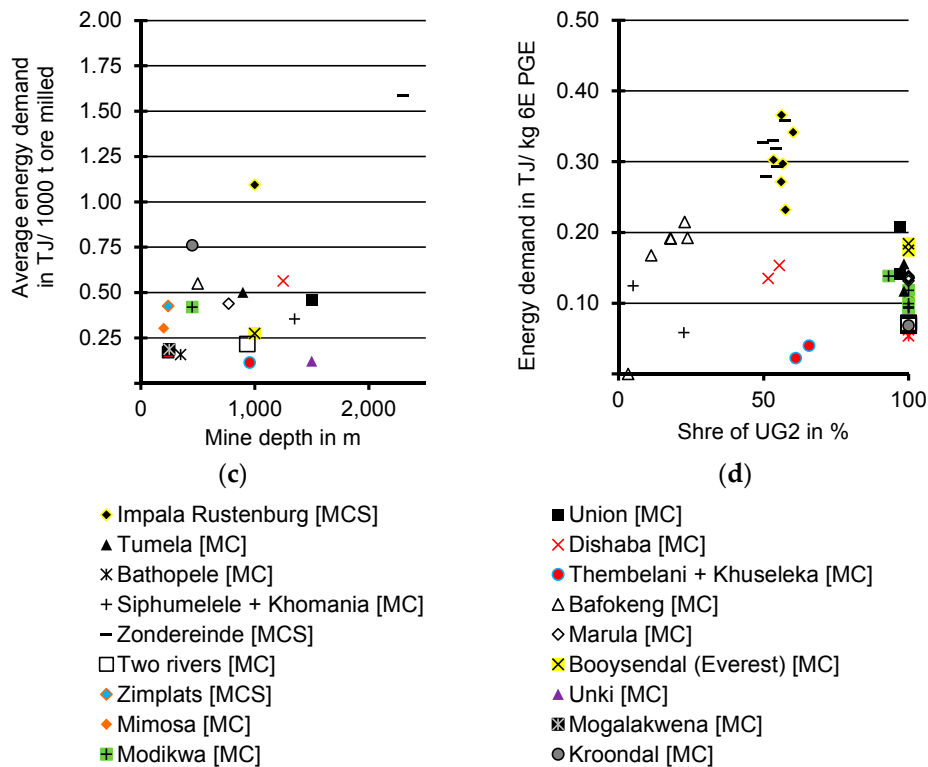


**Figure 5.** Electricity consumption per company: (left axis) per kg 6E PGE; and (both right axis) per 1000 t ore milled. Based on data from [15,54–84].

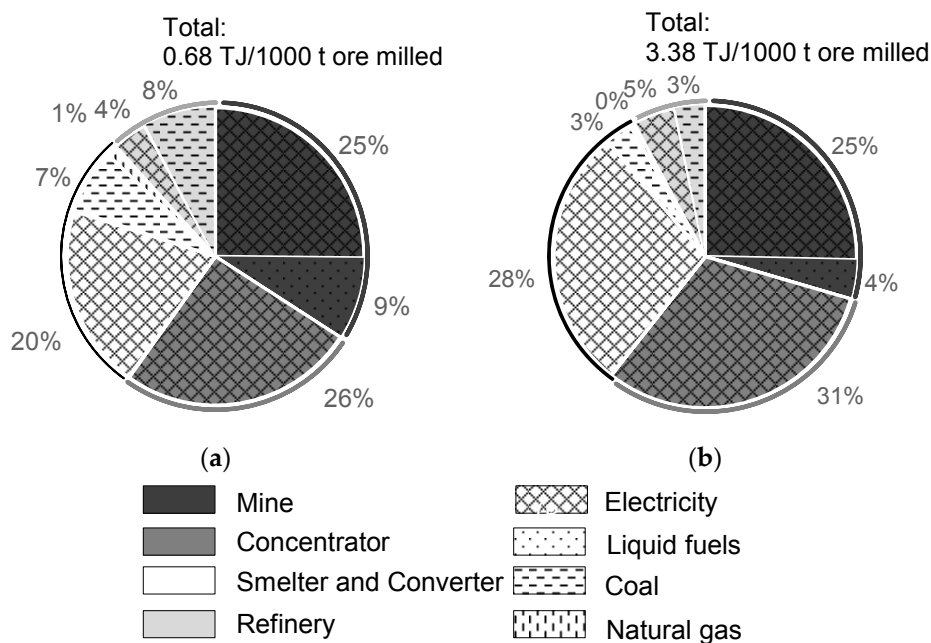
**$CED_{fossil}$ .** Based on the share of energy carriers (Figure 7b), the  $CED_{fossil}$  of different energy carriers (Table S2) and the electricity consumption reported by all companies for 2015 (see above), an estimation of the  $CED_{fossil}$  of PGE production can be derived. In 2015, the overall  $CED_{fossil}$  amounted to 177 PJ. This corresponds to 2.26 TJ and 0.60 TJ per 1000 t ore milled and kg 6E PGE, respectively. The average  $CED_{fossil}$  for the period from 2010 to 2015, resulting from the use of electricity, coal, gas and liquid fuels is 0.67 TJ/1000 t ore (Figure 7b). Due to its high demand of primary fossil energy carriers, electricity consumption presents the major lever to reduce the consumption of fossil energy resources.



**Figure 6.** Cont.



**Figure 6.** Energy demand per 1000 t ore milled and per kg 6E PGE production plotted over head grade (a,b); and per 1000 t ore milled plotted over mine depth (c); and the share of UG2 processed (d). Data from 2010 to 2015. Regression lines and related  $R^2$  can be found in Figures S2–S7. Abbreviations: MC: Mine and concentrator; MCS: Mine, Concentrator and Smelter. Based on data from [59–62,68,69,73,75,85–89].



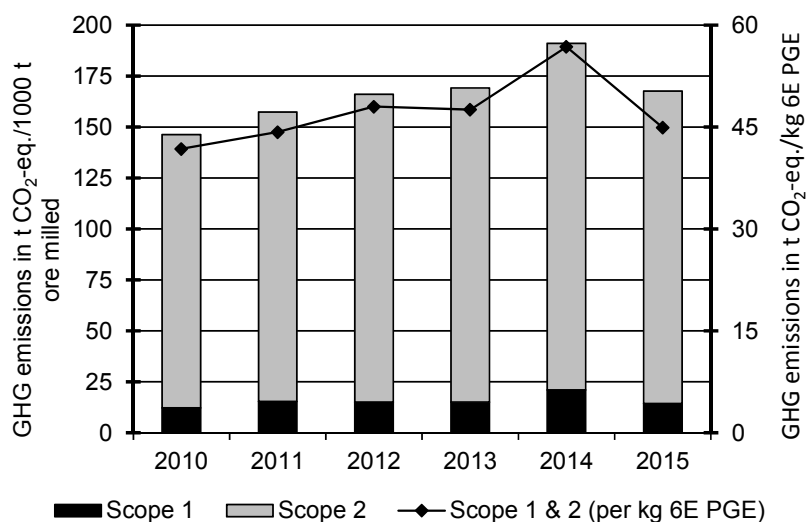
**Figure 7.** Average consumption of electricity, liquid fuels, coal and natural gas 2010 to 2015 for different processing stages (a); and corresponding CED<sub>fossil</sub> (b). Minor shares of other fuels are not depicted. Part (a) is based on data from Anglo Platinum [63–67,90].

#### 4.2. GHG Emissions

In 2015, total Scope 1 and 2 emissions amounted to 13 million t CO<sub>2</sub>-eq. This corresponds to 167.5 and 44.9 t CO<sub>2</sub>-eq. per 1000 t ore milled and kg PGE, respectively. Directly emitted emissions caused by the combustion of fossil fuels (Scope 1) account for only 8% of these emissions. The large share of GHG emissions resulting from purchased energy originates from the high share of coal power used in the South African energy mix: In 2015, 95% of electricity was generated from coal entailing high GHG emissions [76]. This results in a GWP of electricity generation of 1009 t CO<sub>2</sub>-eq./GWh [77]. In Zimbabwe, only accounting for 8% of PGE production, 56% of electricity is from coal, the remainder from hydropower.

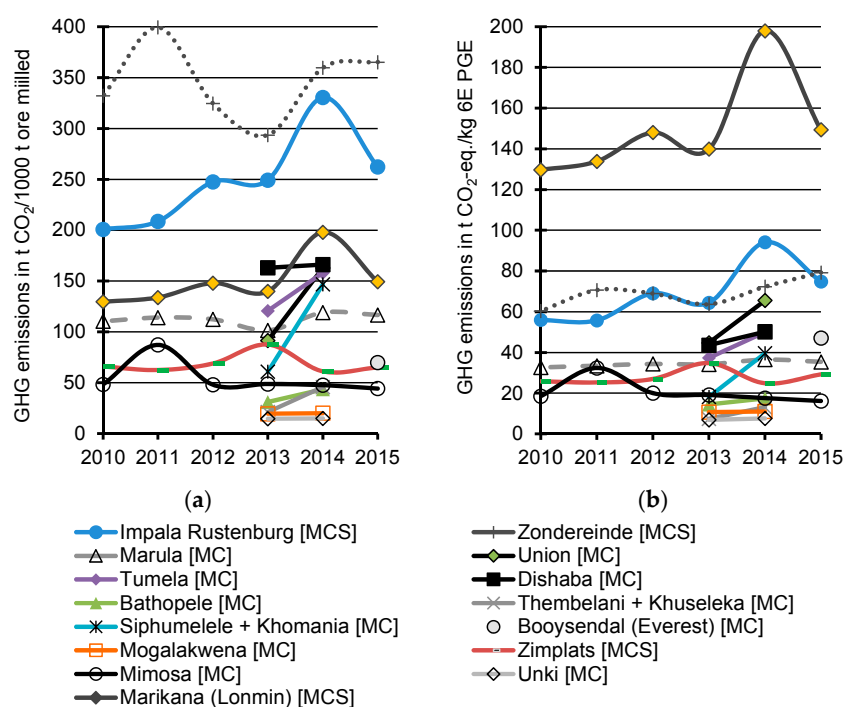
Scope 1 and 2 emissions show a slight, but steady increase per ore milled between 2010 and 2015 (Figure 8): An increase in total emissions can be observed per 1000 t ore milled and per kg PGE. The increasing trend cannot be observed in the case of Scope 1 emissions. The value fluctuates around 15 t CO<sub>2</sub>-eq. per 1000 t ore milled and accounts for less than 10% of total GHG emissions. Emission profiles of PGE companies remain more or less stable, while PGE output per processed material decreases over the long term due to decreasing head grades (see part I [1]).

Other effects, such as the strike in 2014, can clearly be observed in Figure 8. During the strike period, stockpiled (of low grade) material was processed to compensate for production losses. Scope 3 emissions differ by a factor of 100 among PGE producers (Figure S8). In the case of Anglo Platinum, Scope 3 emissions amount to about a quarter of emissions per 1000 t ore milled, whereas all other producers report very low values. Emission profiles of different mines mostly show constant or increasing profiles (Figure 9). Open-pit mines show lowest emissions per processed material. In 2012 and 2014, peaks in emissions can be observed. This is due to low grade material that was processed due to the strike that affected the mining industry. The strike mainly affected Lonmin and Impala Platinum, as can be observed in the emission profiles of the respective mines.



**Figure 8.** GHG emissions (Scope 1 and 2): per t ore milled (left axis); and per kg 6E PGE (right axis). Based on data from [15,54–84].





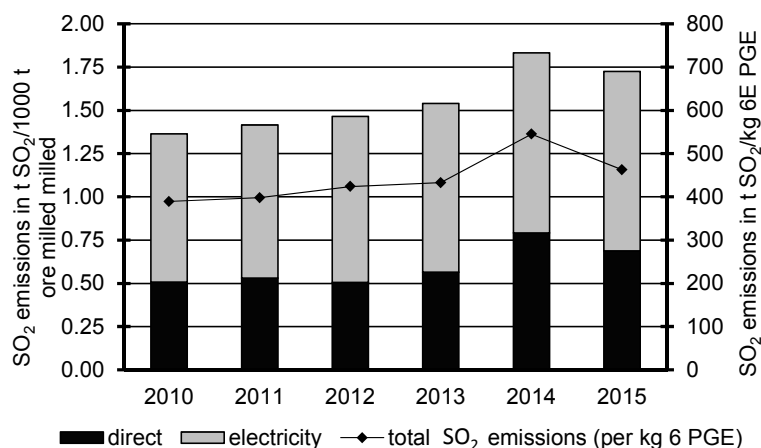
**Figure 9.** GHG emissions for individual mines: per t ore milled (a); and per kg 6E PGE (b). Based on data from [55,57,59–62,68,69,73,75,85–89].

#### 4.3. Sulfur Dioxide

The production of PGE emits large quantities of SO<sub>2</sub> at the smelting complexes. PGE producers only report direct SO<sub>2</sub> from off-gas that is produced in the converting process. However, large quantities of SO<sub>2</sub> are emitted as a consequence of electricity generation (Figure 10). SO<sub>2</sub> emissions from electricity generation amounted to 8.0, 7.6, 7.8, 7.9, 8.6 and 8.1 t SO<sub>2</sub> per GWh in South Africa in 2010, 2011, 2012, 2013, 2014 and 2015, respectively [91]. SO<sub>2</sub> emissions from energy generation in Zimbabwe were adapted according to the share of coal-based electricity generation. In 2015, SO<sub>2</sub> emissions were 1.73 t SO<sub>2</sub> per 1000 t ore milled, or 463 kg per kg PGE. About 60% of these emissions originate from electricity consumption. PGE producers do not report SO<sub>2</sub> related to purchased electricity (or other activities). This emphasizes that the inclusion of electricity-related emissions is required for a comprehensive assessment of emissions. The combustion of liquid fuels only contributes to a minor share (8 kg SO<sub>2</sub> per 1000 t ore milled in 2015).

From 2010 to 2015, emissions have steadily increased from 389 kg to 463 kg SO<sub>2</sub> per kg PGE. The increase in emissions can be attributed to an increase in direct emissions and emissions related to electricity provision, totaling 40 kg and 33 kg SO<sub>2</sub> per kg PGE, respectively. The latter is due to an increase in electricity demand and a slight increase in emission intensity of electricity provision in South Africa [91]. An increase in direct emissions can be ascribed to an increasing share of production in Zimbabwe. Operations in Zimbabwe emit substantially more SO<sub>2</sub> in comparison to facilities in South Africa: the share of SO<sub>2</sub> emissions emitted in by Impala Platinum's facilities in Zimbabwe amounted to 79% of total SO<sub>2</sub> emissions, while the share of production in Zimbabwe only amounted to 36% of Impala Platinum's total PGE production [57]. Thus, an increasing share of PGE production in Zimbabwe, as observed between 2010 and 2015 (see part I [1]), results in an increase in emissions per kg PGE. SO<sub>2</sub> emissions from liquid fuel combustion (assuming the combustion of diesel) range from 6.5 kg to 8.8 kg per 1000 t ore milled (not depicted). Other sources of SO<sub>2</sub> emissions, such as the provision of auxiliary materials only contribute to a minor extent in comparison to direct emissions and emissions from electricity generation. The installation of SO<sub>2</sub> capturing devices presents a way to reduce emissions by a substantial amount: Acid plants are reported to reduce the SO<sub>2</sub> concentration in

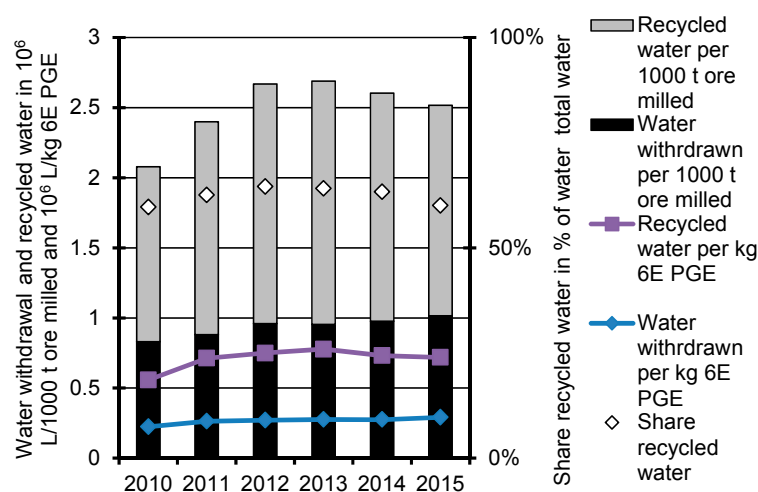
off-gas from 50–70 ppm to 20 ppm by catalytic conversion [92]. Highly concentrated sulfuric acid and gypsum are produced from off- and tailgas cleaning. These scrubbers are in place in several facilities. Therefore, such environmental measures are considered here.



**Figure 10.** SO<sub>2</sub> emissions (direct from converting and from electricity generation): per 1000 t ore milled (left axis); and per kg PGE (right axis). Based on data from [15,54–84,91].

#### 4.4. Water Withdrawal and Recycling

In 2015, water withdrawn amounted to 1.0 million L per 1000 t ore milled corresponding to 0.272 million L per kg PGE. The water withdrawal per kg PGE output and per 1000 t ore processed has increased over the past years from 0.83 million L in 2010 to 1.02 million L in 2015 (Figure 11). Likewise, the use of recycled water increased from 1.25 to 1.50 million L per 1000 t ore milled, corresponding to 0.356 and 0.402 million L per kg 6E PGE, respectively. The share of recycled water fluctuated between 60% and 65% of total water used (withdrawal + recycling). Ranchod et al. [93] assessed the water footprint of a platinum mine and found that the water footprint is dominated by the processing plants and tailing dams, accounting for 47.3% and 43.3% of the water footprint, respectively. Evaporation losses and entrainment losses during tailings discharge account for 23.7% and 19.4% of the water footprint, respectively [93]. In recent years, the mining industry focuses on shifting from potable water to recycled process water in order to save water resources and to reduce costs. However, the data outlined above show an increasing trend in water demand.



**Figure 11.** Water withdrawal, recycling in million L per 1000 t ore milled, per kg 6E PGE (left axis) and share of recycled water (right axis). Based on data from [58,59,62,63,68,69,71–73,79–84,89].

## 5. Discussion

The analysis of emissions, water use and electricity demand from 2010 to 2015 reveals increasing trends for all assessed indicators (except for PGE production) (Figure 12). Despite year-to-year fluctuations, clear upward trends can be identified. Ore grade and production volumes fluctuate but remain more or less stable during the assessment period. In recent years, positive trends in electricity demand, GHG emissions, SO<sub>2</sub> emissions and water consumption per unit output can be observed. The energy per unit output is increasing while most of electricity in South Africa is supplied by coal-powered plants entailing consequences for the emission of GHGs, SO<sub>2</sub> and other pollutants. Results reveal that electricity-related SO<sub>2</sub> emissions account for 60% of emissions. PGE producers usually do not report these emissions and only the assessment of a wider scope reveals that these emissions exceed those directly emitted by PGE producers. An explanation for increasing emission trends and energy demand is the increasing effort to hoist the ore. Furthermore, the share of UG2 ore that is processed (part I [1]) increased, resulting in higher energy demands (Section 3.3) and emissions related to energy provision.

Declines in production and ore grade, as well as increase in emissions and energy demand can be observed in 2012 and especially pronounced in 2014, when the South African mining industry faced severe strikes. The strike of mine workers resulted in a shortage of hoisted ore, resulting in stock piles (of less valuable) material that was processed.

To alleviate negative effects originating from decreasing ore grades, several options are given:

- The introduction of energy savings measures and renewable energy sources reduce the (fossil) energy consumption and emissions related to energy generation (e.g., [94–96]).
- The use of fuel cells [57].
- In South Africa, the introduction of a carbon tax is envisaged that will put pressure on energy provision and PGE production to reduce GHG emissions. However, the tax has not been implemented yet.
- The improvement of off-gas cleaning or a change in the smelting/converting process, e.g., use of *ConRoast* process, allows the reduction of direct SO<sub>2</sub> emissions [97]. In this process, the smelting process is not a sulfur-based smelting process and sulfur can be removed prior smelting by a fluidized-bed roaster.
- The South African government started implementing programs to increase environmental regulation such as controls on air and water quality and emissions of GHGs and to improve other aspects of sustainable development such as social and economic aspects (e.g., [98,99]).
- Likewise, the introduction and enforcement of strict emission regulations is required in Zimbabwe to lower emissions: SO<sub>2</sub> emissions per kg PGE are substantially higher in Zimbabwe than in South Africa (see Section 4.3). The fact that similar production steps are applied in both countries clearly indicates that reasons for higher SO<sub>2</sub> emissions are not of a technical nature.

Results presented in this study cover the majority of PGE production in Southern Africa. For all indicators except CED<sub>fossil</sub>, at least 66% of the production is covered (Figure S1). Thus, results can be considered representative. The data coverage does not give an indication on data quality or completeness. Companies might change the scope and way of reporting of those aspects analyzed within the current paper over time [3]. Nevertheless, sustainability reports are audited by external bodies to ensure data completeness and quality. Furthermore, data were added to increase the completeness, e.g., indirect SO<sub>2</sub> emissions. Therefore, we consider the presented data to be the most up-to-date and complete report of the analyzed indicators available.

In contrast to reported ore grades in the current assessment, decreasing ore grades can be observed in the long term [4,6]. A comparison with other published literature shows that results differ by less than 20% from results presented by Glaister and Mudd [6] and from the Ecoinvent database [7,100] for all assessed indicators except water withdrawal (Figure 13). An extrapolation of values reported in Glaister and Mudd [6] assuming average annual growth rates between 2010 and 2015 and using

2008 as a base year shows that GHG emissions and energy demand reported in the present assessment are plausible continuations of previous findings. The emissions of SO<sub>2</sub> reported in the Ecoinvent database stems from a report published in 1997 [8]. Since then, emission legislation has tightened and the platinum industry has undertaken efforts to reduce emissions by installation of acid plants or the change in processing steps [101,102]. Re-design of process steps and installation of abatement technologies reduce emissions rapidly. The observed increase in emission is thus a phenomenon that might still occur due to other reasons that take place over time such decreasing head grades, SO<sub>2</sub> content of the processed ore, etc. Water withdrawal is lower in the present results than in comparable literature. This might be due to differing assessment scopes and water flows that are considered [3].

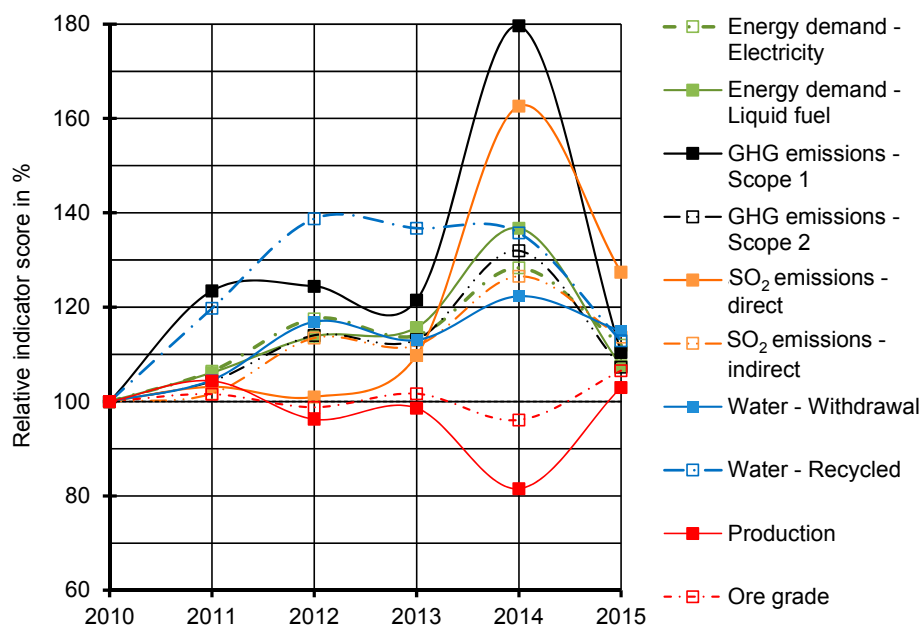
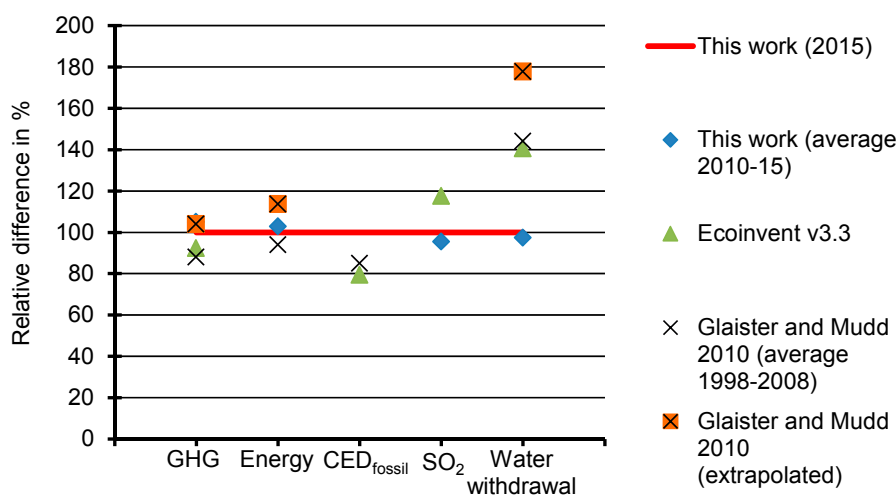


Figure 12. Change in indicator scores in percent from 2010 to 2015 (2010 = 100%).

## 6. Conclusions

Due to the nature and characteristics of PGEs, it is challenging to substitute PGEs in many (industrial) applications and, thus, PGEs are often an indispensable component. For instance, PGEs are used in many (novel) technologies that promise a more sustainable future of transportation and energy provision, e.g., in exhaust gas catalysts for vehicles and fuel cells. Thus, the future demand for PGEs is predicted to increase worldwide. The present study was designed to determine the effect of PGE production in Southern Africa (where most of today's supply originates from) in terms of environmental aspects to support the environmental assessment of technologies using PGEs. The assessment is mainly based on data reported by PGE producers and is complemented by scientific literature to provide the most comprehensive image of environmental impacts possible. Whenever possible, indicators are reported to be used in LCAs focusing on the use of PGE by providing commonly used indicators (global warming potential, CED<sub>fossil</sub>). Future work should try to include other emissions contributing to certain impact categories (e.g., acidifying emissions other than SO<sub>2</sub>) or add local data on water availability and quality to allow the determination of other specific life cycle indicators. In regards to SO<sub>2</sub> emissions, it can however be assumed that reported SO<sub>2</sub> emissions present the major part of acidifying emissions. Future work should seek to compare provided data with data that are compiled on an individual process step basis to allow a more detailed assessment of environmental implications of different processing steps and applied technologies. The results of this investigation show that the provision of PGEs utilized in these technologies emits substantial amounts of emissions and requires large quantities of energy. Furthermore, the results presented

here suggest that improvements in PGE production efficiency and reduced energy demand will generally reduce environmental impacts of PGE production as many indicators are directly related to the energy demand. From a global perspective, presented results are especially relevant in regard to GHG emissions. Many novel technologies using PGEs aim to reduce the consumption of fossil energy carriers (e.g., fuel cells) or to improve process efficiencies (e.g., PGE-based industrial catalysts) and thereby to lower GHG emissions. Increasing emissions, as revealed in this paper, might even outweigh the benefits of using PGEs in such applications. This implies that, apart from the optimization of PGE production, the use of secondary PGE should be increased (which is challenging in the case of a strongly increasing demand) and the overall use of PGEs in these technologies should be lowered. From a local perspective, SO<sub>2</sub> emissions and water demand present important aspects that severely affect the local population. In both cases, improvements can be achieved through process optimization and the enforcement of strict regulations. These findings gain importance in face of decreasing ore grades that are reported in the long term. This will eventually lead to a further increase in emissions and resource demand due to larger quantities of material that need to be processed.



**Figure 13.** Comparison of GHG emissions, energy demand, CED<sub>fossil</sub>, SO<sub>2</sub> emissions and water withdrawal. Results are compared to reported values of Glaister and Mudd [6] and the Ecoinvent database [7,100]. Data and assumptions can be found in the Supplementary Materials (Table S3).

The observed increase in indicator scores underlines the importance of analyzing data for a period of time, as opposed to providing a single result based on average data. Thus, the analysis of the environmental performance of (novel) technologies should seek to include the most data available. From presented production statistics (part I [1]) and environmental data, it can be concluded that substantial efforts are required to improve the environmental performance of PGE production in the context of current market conditions, the existing energy sector and the political framework. Further research is required (and precise data need to be collected) for a more detailed assessment of environmental indicators of each processing stage allowing the identification of optimization strategies. In all likelihood, a combination of improvements in mining and processing technology (e.g., smelting technology), waste management and pollution abatement will be the key to ensuring sustainable PGE production in Southern Africa and worldwide in the future.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2075-163X/7/11/225/s1>, Excel document containing most important data presented in this article, Table S1: Results allocated by average price (2010–2015), Table S2: CED<sub>fossil</sub> of different energy carriers, Table S3: Comparison to other studies, Figure S1: Data coverage in percent of production, Figures S2 to S7: Linear regression analysis of energy demand. Figure S8: Scope 3 GHG emissions.

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