PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE, 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

Feasibility of solar photovoltaic energy as an energy source for the electrowinning of zinc in South Africa

Ricardo Magdalena[a], Nicole Uys[b], and Jochen Petersen[c]

[a] Research Centre for Energy Resources and Consumption (CIRCE) - Universidad de Zaragoza, Zaragoza, Spain; rmagdalena@unizar.es CA
[b] Mineral to Metals Initiative, Department of Chemical Engineering, University of Cape Town, Cape Town, South Africa, uysnic002@myuct.ac.za
[c] Mineral to Metals Initiative, Department of Chemical Engineering, University of Cape Town, Cape Town, South Africa, jochen.petersen@uct.ac.za

Abstract:

Energy consumption for metal extraction and beneficiation is substantial and is expected to keep growing due to increased demand. With rising worldwide energy prices and the continued energy crisis in South Africa, there is a need to decrease the dependence on the national energy grid. Among the refining processes, electrowinning is one of the most energy intensive unit operations. In the context of zinc, electrowinning can consume on average 2,900-3,300 kWh/t-zinc, approximately accounting for 60% of the total electricity consumption of refined zinc production. Industrial and economic growth, a major focus of Southern African countries, is positively correlated with zinc demand due to its role in general construction, electricity transmission, and telecommunications. South Africa is endowed with 14 Mt of zinc content within 200-300 Mt of zinc ore reserves and expanding internal zinc production capacity is a current focus. Since electrowinning units operate with low-voltage direct current, photovoltaic solar energy appears to be an applicable green energy source due to its electricity output also being low-voltage direct current. In addition, South Africa has an attractively high solar irradiance (220 W/m^2 compared with Europe's 100 W/m^2). Hence, an investigation into the technical and economic feasibility of substituting or supplementing the energy demand, using solar energy for the electrowinning unit of a theoretical zinc refinery operating in the Northern Cape of South Africa, is warranted. A high-level carbon footprint analysis is included. The findings from this study could assist in stabilising the energy supply for the beneficiation of zinc in South Africa, as well as contribute to the decarbonisation of the industry.

Keywords:

Zinc refining, electrowinning, solar energy, photovoltaic cells, South Africa

1. Introduction

The applications of metals within society are ubiquitous [1]. This continued, and increasing, demand for metals results in a substantial consumption of energy related to metal extraction and beneficiation. The embodied energy associated with metal production (mining, beneficiation and refining) can range from 20 MJ/kg refined metal (Pb, steel) to 200 MJ/kg refined metal (Al, Ni) and should be taken into consideration in conjunction with the annual production of metals when determining the total annual energy consumption per metal. While mining is reported to account for between 2-11% [2] (average reported value is 3.5% [3], [4]) of total global energy consumption, the energy consumption associated with metal refining processes (leaching, smelting, electrowinning etc.) typically far exceed that of mining activities. For instance, the following metals and alloys, namely copper nickel, zinc, lead, aluminium and steel, collectively consume approximately 6% of the annual global energy production, while depending on the source of energy production, they can account for up to 10% of the global greenhouse gas emissions [5], [6].

The following trends are the major driving factors for the increasing metal demand: population growth, increased urbanisation, electrification and renewable energy technologies [7], [8]. In conjunction with the United Nations prediction [9] that in the next 30 years the world's population may increase by 2 billion people, the World Bank [10] anticipates that the urban population will more than double by 2050. In order to accommodate this trend, there will be a focus on building infrastructure which will increase demand for certain metals, such as zinc (galvanised steel) [11]. In addition, societies focus on electrification, in the aim of achieving carbon neutrality, will not only increase demands for metals associated with green energy generation technologies but also on those for energy storage [12], [13]).

 https://doi.org/10.52202/069564-0161

Several authors have already studied and predicted this increasing demand [14], [15], with Figure 1 illustrating the predictions from the last decades until 2100 [1]. Other authors have corroborated these trends with predictions for zinc [16] and copper [17] being of the same order of magnitude. This increased demand for metals will translate into increased metal production. However, one must ensure this is achieved in a 'sustainable' manner with due regard for the sources of energy used which will impact the industries' energy stability and carbon footprint.

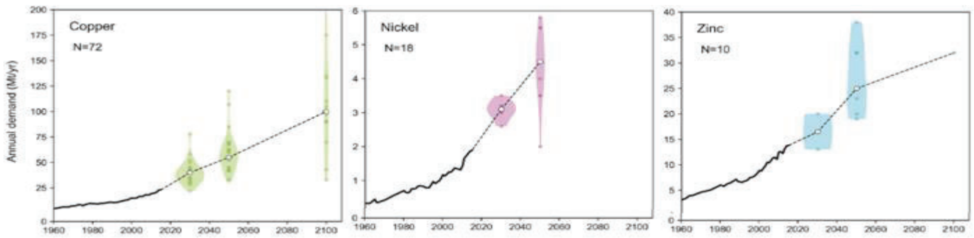

Figure 1. Historical and projected future outlook demand for copper, nickel and zinc from 1960 to 2100 [1].

To meet the demand created by electrification and population growth the global power consumption is also projected to increase by 50% between 2020 and 2050 [18], [19]. However, the world is currently in a Global Energy Crisis [7]. What started in 2021 as a supply and demand imbalance, emerging out of the COVID pandemic, has been exacerbated, primarily, by the invasion of Ukraine by Russia in February 2022. As Russia is seen as the world's largest exporter of fossil fuels and thus the interplay of sanctions and supply curtailment has exposed Europe's historic dependence on Russia for natural gas, oil and coal [7]. In some countries additional environmental factors such as droughts (Brazil and China) have also contributed to the crisis at a more local scale [20]–[22]. As a result of the current Global Energy Crisis there has been a high volatility in the prices for metals, gas and electricity. As a result of the high electricity prices, there are refineries in Europe which have been forced to either halt or reduce production capacity. The Budel refinery in Belgium, from the company Nyrstar, is one such example [23]. The IEA emphasised that this energy crisis is not a "clean energy crisis" as it believes the world should be relying on larger quantities of "green energy" to address this crisis and thereby creating more secure energy systems [7]. The hope is that this Global Energy Crisis will serve as a catalyst for policy makers and consumers to fast track the implementation of renewable green energy technologies.

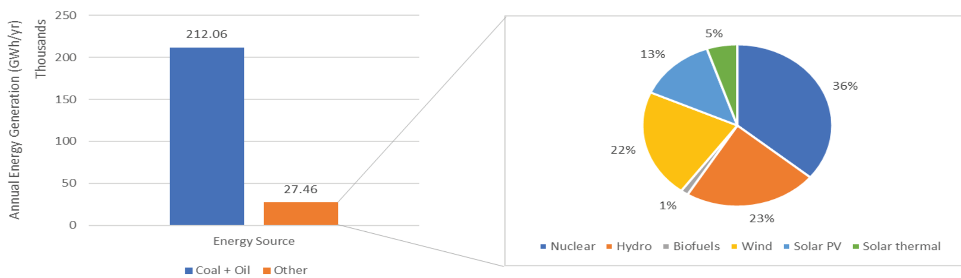

Figure 2. Annual electricity generation (in thousands of GWh/yr) by source, in South Africa in 2020. Energy sources, other than coal and oil, are characterised further by % [7].

South Africa is also facing an energy crisis, although this crisis predated the current Global Energy Crisis. In 1998, a White Paper on the Energy Policy of the Republic of South Africa predicted that electricity demand would exceed generation capacity by 2007 [24]. As this warning was not heeded, the country started experiencing nationwide blackouts (referred to as load-shedding) in the latter part of 2007 and which continues to this day. Eskom is the state-owned utility company which has a monopoly on the electricity generation within South Africa, which is also highly centralised. The country has historically and continues to be primarily reliant on coal as its source of electricity generation [7]. As of 2020, coal represents 88% of energy generation, with nuclear and renewables representing 4% and 7% respectively (Figure 2). This is in comparison with the world average dependence on coal being 36.5% and renewable energies being 26% [25]. Despite South Africa's attractively high solar irradiance (220 W/m2 compared with Europe's 100 W/m2), solar PV only represents 1.5% of the electricity generation capacity at an estimated 3600 GWh/yr [24], [26]. The authors believe the application of solar PV within the local metals beneficiation and refining industries represents an opportunity for South Africa.

At the end of 2007, the National Energy Regulator of South Africa (NERSA) commissioned a Renewable Energy Feed in Tariff (REFiT), which was approved in March 2009, as a mechanism to promote the generation of renewable energy within South Africa by creating certainty for investors. Effectively the REFiT was a purchase power agreement at fixed prices, which varied according to the renewable energy source. As of 2008, over 36 other countries (including Spain, Germany, certain states in the USA, Brazil, and even Kenya) had REFiT's [27], [28]. However, in 2011, the Department of Energy revised this scheme and replaced it with a more conventional procurement process, called the Renewable Energy Independent Power Producer Programme (REIPPP), which was based on a competitive pricing model, where independent power producers bid for the development of renewable power plants [28].. In particular, the application of Feed in Tariff (FIT) for small-scale embedded generation systems (SSEG) rests with the individual municipality / city. The City of Cape Town (CoCT) is one of the few South African cities which has successfully implemented a FiT for SSEG where households can receive approximately 0.04 $/kWh with the caveat that the household/business must be a net consumer of electricity (from the CoCT) over a 12-month period.

Load-shedding is a scheduled means of rotating the available electricity amongst Eskom's customers. The reason load-shedding is implemented is to prevent the entire electricity system from failing [29]. As a result, mining contracted by 9% in 2022 and many industries and companies are at the point of closure [30]. The need to stabilise the national energy system and ensure stability of energy availability is paramount to the minerals and metals industry. In response to their inability to provide a stable power supply and to incentivise private sector participation in addressing the continued load-shedding, in 2021 the South Africa government increased the embedded generation (self-generation) capacity licensing threshold from 1 MW to 100 MW [31].

While there are many metals which could be considered within the South African context, the refining of zinc has been chosen for this particular study. Zinc is the fourth most consumed metal globally [32] and as it readily reacts with oxygen, forming a protective zinc oxide layer, its primary use (>50%) is for galvanising of steel [33]. Other major uses include zinc-based alloys and brass production [33]. For the same aforementioned reasons that metal demand is expected to increase, the demand for zinc is also expected to increase. Zinc demand has been positively correlated with industrial and economic growth by White [34] and as both are key focus areas for Southern African countries the demand for zinc consumption is expected to increase. In order to obtain zinc at an economically competitive price, the focus on local production is expected to increase. South Africa is endowed with 14 Mt of zinc content [35] within 200-300 Mt of zinc ore reserves [36] which it is in the process of beneficiating (at Gamsberg with proposals to re-explore the Prieska Copper-Zinc Project). However, since the closure of Exxaro's Zincor Plant in 2011/2012, it no longer locally refines zinc metal. Zincor closed due to rising 'administrative costs', of which a contributing factor may have been the 2008/2009 zinc metal price depression [37] and in addition is speculated to have been due to rising electricity costs [34]. Given the renewed interest in exploring the refining of zinc and given the current energy supply crisis faced by the country, it is proposed to explore the potential application of solar PV within the zinc refining process within the context of South Africa.

The most energy intensive step in the traditional refining process (Roast-Leach-Electrowinning process) for zinc is electrowinning, which uses direct current (DC) to deposit zinc, typically from a purified zinc sulphate solution, onto cathodes. It consumes on average 2,900-3,300 kWh/t-zinc, accounting for approximately 60% of the total electricity consumption of refined zinc production [38]. As photovoltaic (PV) systems represent an established 'green' energy technology to produce DC electricity, it appears that a solar PV system is the most appropriate 'green' technology to generate electricity for this purpose. The application of solar PV for the provision of electricity for the zinc electrowinning unit operation would mean that losses in the electricity generation system would be minimised as no rectification from DC/AC is required, contributing to energy efficiency and loss minimisation, as well as contributing to the decarbonisation of the industry.

2. Case study

As previously mentioned, the Minerals Council of South Africa estimates that South Africa has 14 Mt of zinc content [35] within its 200-250 Mt of zinc ore reserves with the Northern Cape Province (specifically near the mining town of Aggeneys) containing significant deposits of these Lead-Zinc ores [39]. In particular the Gamsberg deposit, located approximately 30 km from Aggeneys, which is one of the largest zinc deposits in the world, is estimated to have approximately 12.8-13.9 Mt of Zinc content within its 214 Mt ore body (6-6.5% Zn) and a life of mine (LoM) of over 30 years [40]. As this one area accounts for nearly all the estimated zinc content within South Africa it is the most likely location for a future zinc refining facility and will thus form the focus area for this case study. This theoretical refinery, proposed in this study, would use the Roast-Leach-Electrowinning process, as this process accounts for 80-95% of all zinc production, with a production capacity of 50,000 tons of refined zinc per year. As zinc refineries can range in capacity from 30,000 tons refined zinc produced per year to 450,000 tons per year, the proposed 50,000 tons per year would be considered a small refinery.

Aggeneys is a copper, zinc, silver lead mining complex and was developed to service the Black Mountain Mine. Vedanta is the current majority owner of both Black Mountain and Gamsberg. With respect to climate Aggeneys is classified as semi-desert [41] and water is pumped from the Orange River (approximately 40 km away). In terms of Photovoltaic Power potential, Aggeneys is one of the world's prime locations with high solar irradiance (daily totals of 5.6 h corresponding to approximately 2,000 kWh/kWp) [42].

https://doi.org/10.52202/069564-0161

There is already a 46 MW (117 GWh/yr) solar PV power project which was commissioned in July 2020 in Aggeneys (Aggeneys Solar PV Park) and is designed to power 20,000 homes. It is owned by BioTherm Energy, cost $54.7m to build, and has a 20-year contract with Eskom under a power purchase agreement. It consists of 140,640 single axis tracking polycrystalline silicon PV modules and covers an area of 110 hectares [43]. This indicates the theoretical feasibility of designing and installing a solar PV plant in this location and the possibility of power purchase agreements with Eskom to possibly sell excess energy back to the grid if need be.

3. Methodology

Traditionally, solar resource / solar irradiance maps, which provide the average available hours of sun per day, were used for this purpose. However, there are now software packages available which can provide this and other important data, such as irradiance depending on the angle, azimuth, temperature, etc. Once the location, in this instance the Northern Cape, and other parameters such as the angle and azimuth are identified, it is possible to obtain the data monthly, daily, or even hourly. The software used in this project was the Photovoltaic Geographical Information System (PVGIS), provided as a free tool for the European Commission (EC) and the Joint Research Centre (JRC). As a general rule, solar PV installations located in the Southern hemisphere must face North (Northern hemisphere must face South) in order to maximise the amount of irradiation received. Furthermore, depending on the purpose of the installation, the slope angle must be equal to the latitude, or plus / minus 10º, depending on whether more irradiation is required in winter or summer.

For this study, the azimuth chosen is 180° (North facing), while the optimum angle, determined after a sensitivity analysis carried out, has been set up as 30°. This sensitivity analysis is shown in Figure 3, where it is possible to see the irradiation with different azimuth and angles. There are two figures which illustrate the best configuration in terms of azimuth. As can be seen, Figure 3a (left) has the least variance, having more or less the same irradiation during the whole year. Conversely, Figure 3b (right) shows an inverted Gauss bell, obtaining high irradiation (>265 kW/m2) during the summer months (from October to March), while in winter months (from April to September) the irradiation is very low (<20 kW/m2). Since the electrowinning plant is designed to work during the whole year, the most applicable configuration is Figure 3a (180° azimuth) which results in approximately the same amount of irradiation every month of the year (i.e. least deviation from the average irradiance value).

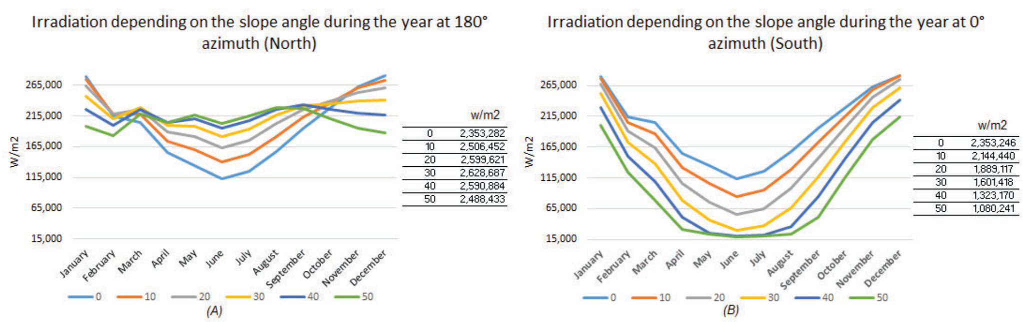

Figure 3. Annual irradiation in the Northern Cape, South Africa, with two different angles of azimuth chosen (180º and 0º). Tables on the right of the Figures summarize the total amount of irradiance per year depending on the slope of the solar panels.

Once the azimuth has been chosen, the angle of the solar panels needs to be determined. As aforementioned, this slope can vary according to the specifications of the facility. For the purpose of this study, the best configuration will be considered as the one with the highest irradiance. Thus, it has been decided to use all the irradiation for every hour in the year 2020, to obtain the cumulative irradiation at the end of the year. As it is possible to see in the data table included in Figure 3a, the highest irradiation occurs when the solar panels are inclined 30º. Therefore, and following this criterion, the configuration chosen for the solar plant is 180º for the azimuth, and 30º for the slope.

Different scenarios have been identified to analyse the performance of the solar plant according to the power installed and the operating time. Currently, the plant is assumed to be operating 24 h/day. However, this is not possible to carry out a 24h/day operation exclusively using solar PV technology as other technologies would be needed to supply electricity during the night, either as power generation (grid supply) or additional storage capacity (batteries).

Accordingly, two more scenarios have been analysed to determine the feasibility of the plant with respect to its hours of operation, while keeping annual zinc production the same. The first is operating the electrowinning plant for only 6 h/day. This operation time is designed around maximising the hours of sun per day that is possible to obtain, during wintertime. This means that even in winter it could be possible to produce the quantity of zinc required, with the possibility of increasing the operation time in summer months, as more hours of sun per day are available. The second scenario is operating for 12 h/day and trying to strike a balance between maximising solar PV electricity generation while balancing the costs of storage capacity / alternative energy sources. In this way, it has been proposed that there will be three different operating durations for the electrowinning plant: 24 h/day, 12 h/day, and 6 h/day.

The electrowinning plant is designed to achieve a production of at least 50,000 tons per year, which is the current production, operating 24 h/day. For all scenarios considered, this annual production value must be reached by the end of the year, irrespective of whether operation times change. For that purpose, if the operation times are reduced, the capacity of the electrowinning plant must be increased, being multiplied two times if the operation time is reduced to 12 h/day and four times if the plant is reduced to 6 h/day. With the above three different operating time scenarios, an energy and economic assessment will be carried out taking into account that the scenarios are applied in the following cases: 1) Grid tie only (basis for comparison as this is the benchmark), 2) Solar plant and grid tie, 3) Solar Plant and Batteries (off grid), 4) Solar Plant with no Batteries (off grid).

3.1. Grid tie only

Electrowinning units worldwide are typically connected through a country's national / regional electricity grid. Grid tie is therefore the benchmark for all other scenario comparisons detailed below. Since no additional technologies (additional energy generation nor energy storage) are used in this option, the electrowinning process will be designed to operate 24 h/day. The capacity of the plant would be costed for a production of 50,000 tons refined Zn/day. The economic assessment in this case, in terms of electricity cost, would be simply multiplying the electricity demanded by the electrowinning plant with the current price of the electricity. Operating the electrowinning plant 12 h/day or 6 h/day would result in an unnecessary doubling and quadrupling of the capacity of the electrowinning unit, if the same annual production is to be achieved. In this event, the economic assessment would be calculated similarly to the 24 h/day case, however, additional electrowinning capacity would be needed (increased CAPEX costs), solely increasing the final economic costs without any perceived financial gain.

3.2. Solar PV plant and grid tie

This scenario is the most widespread when supplementing electricity supply with solar PV, in particular for households and businesses that are located in close proximity to the grid. This scenario combines a new solar PV plant with the traditional way of obtaining electricity from the grid. One of the main reasons to keep the connection to the grid, is to ensure that in principle there will always be electricity for the plant. This assumes there is no load-shedding. The grid connection mitigates a scenario where there is a drop in embedded generation due to cloudy and rainy days and accommodates for during the night without the necessity to invest in storage capacity or other power generation technologies. It is anticipated that all three operation times are applicable and achievable with this configuration. When the operation times are reduced, the capacity of the electrowinning plant must increase in order to reach the required production throughput. In addition, the power capacity of the proposed solar PV plant must increase in order to produce the increased electricity supply required to maintain annual production. Therefore, the CAPEX of the additional electrowinning units and the increased size of the solar PV plant must be included and added to the final price calculated. This scenario is therefore about balancing the increased capital expense of an increased electrowinning plant and increased solar PV plant with a lower payment for electricity from the grid. The break-even point of each of these scenarios would need to be determined.

3.3. Solar PV plant and batteries

There are currently limited technologies available for storing energy at large scale. The largest being dammed hydroelectricity, however, this application is location specific requiring the available land and water to make it viable. As Aggeneys is classified as semi-desert, dammed hydroelectricity production does not appear to be a viable option. Another option which is starting to make an appearance within the mining industry is the production and storage of hydrogen with excess electricity which can then be converted back to electricity when needed. This should be explored further in future studies, particularly for large scale projects. Although batteries are capable of storing a certain amount of energy, they are widely used in small (household) solar plants. They are unfortunately still very inefficient, since batteries based on lead cannot be discharged more than 40%, while those based on lithium it is possible to use up to 80% [44]. Depending on the type of battery utilised, some metals used for their manufacture are classified as 'critical' and may therefore be expensive due to limited supply. Despite their high cost, batteries were deemed by the authors to be the simplest storage option for this study.

There are different technologies in batteries that can be applied to store energy. The most known are the based on lead-acid (considered the traditional) and those based on lithium [44]. The batteries based on lead-acid are very inefficient since they cannot be discharged more than 40%, otherwise the lifespan could be shortened, being already not very long, since the best technology for this kind of batteries is gel, with a lifespan lower than 750 cycles [44]. On the other side, batteries based on lithium have an efficiency higher than 80%,

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spotting the LTO (variation of the crystalline structure), which has a lifespan higher than 5,000 cycles [44]. The main disadvantage of this battery is that is very expensive (six more times than lead-acid), and this can increase the initial investment. However, this study, lithium batteries have been chosen due to them being the most efficient energy storage system. However, other options should be explored in future studies.

3.4. Solar PV plant with no batteries

This option would only make sense for the configuration of the lowest operation time, namely 6 h/day, since 12 h/day and 24 h/day would inherently require a storage capacity or an alternative source of energy supply because the sun is not available for that length of time. Running an electrowinning plant solely with a solar plant must therefore be carried out during the day, when the sun is shining. The reason for proposing this scenario is due to the well-known fact that batteries (energy storage) represent a significant cost and therefore the feasibility of operating without storage capacity was proposed. However, given that solar irradiance fluctuates within a day and with the seasons, it is already known that a consistent throughput is impossible to maintain. The authors are not anticipating that this scenario will be technically feasible to achieve without a more detailed design where throughput can be increased during the peak solar irradiance hours.

4. Design and performance of the plant

4.1. Power of the solar PV plant

The capacity of the solar plant will dictate the amount of electricity which can be generated. For this study, the solar plant must be designed to achieve the production expected at the end of the year, namely 50,000 tons of refined zinc. The first step to start the design is calculating the power capacity. To that aim, it is needed to convert the zinc generated at the end of the year into power units. It has been taken from the literature review the specific energy to produce 1 ton of zinc in an electrowinning cell, being a range from 2,900 kWh to 3,300 kWh. 2,900 kWh was chosen as the best-case scenario for the initial investigation. If these values are multiplied by total annual tons of zinc produced and divided by the total hours working during the year (the current operation time is 8760 h/yr), it is possible to determine the power needed in 1 h (see Equation 1).

$$Power\ Demand = \frac{50{,}000\ tons\ Zn \times \frac{2{,}900\ kWh}{tons\ Zn}}{8760\ h} = 17\ MW \quad (1)$$

This means that it is necessary to install a solar plant of 17 MW to achieve the specified zinc production. However, and for the reasons explained in the next section, this power must be higher due to losses incurred, as well as the fluctuating electricity produced during the day and depending on the season. To determine the most appropriate power capacity for each of the three operation times proposed, Figure 4 has been presented.

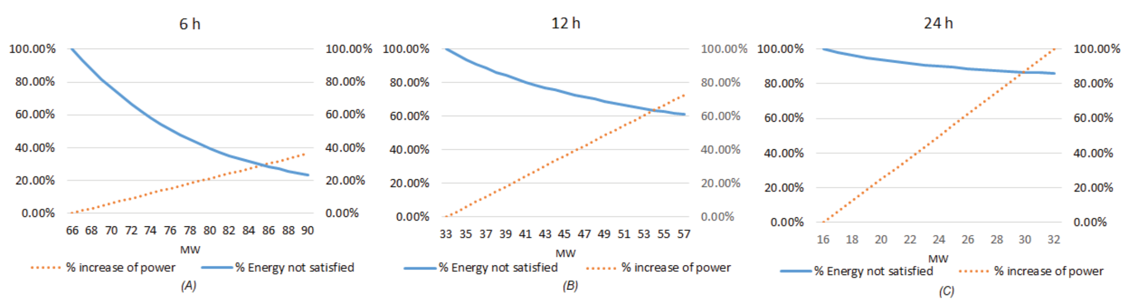

Figure 4. Comparison between the increased power capacity of the solar PV plant (left axis) with the electricity demand not-satisfied by the solar plant as a % (right axis).

As shown, the power required for 24 h operation starts with the 17 MW calculated, while for the 12 h and 6 h are 33 MW and 66 MW, respectively. From these power capacities, as a starting point, the power capacity will be linearly increasing and compared with the electricity not-satisfied from the solar plant, starting at 100% and being reduced when the power installed increases. The electricity not-satisfied can be defined as the electricity needed to supply from another alternative source, either from a green energy or from grid, due to the solar plant not being able to supply all the electricity demanded at certain times.

Although it would make sense to choose the best/optimal power capacity of each solar PV plant as the point at which a % increase in power capacity is no longer greater or equal to the % decrease in energy not-satisfied, given the curvature of the graph, this point is reached very quickly with the 12 h scenario and is never possible with the 24 h scenario. The optimal/best power capacity was therefore chosen as the intersection point between the curve for energy not-satisfied and the line for increasing power capacity of the solar PV plant. The authors felt that for this high-level study this approach balanced the increasing CAPEX association with increasing the power capacity of the proposed solar PV plant while still achieving a reasonable electricity production.

In this way, it is seen that for the 24 h operation time it is needed to increase the power by 90%, to 30 MW, to reduce this electricity by approximately 20% (i.e., 80% of the energy requirements are still not-satisfied). In the case of the 12 h operation time, the power must be increased by 60% approximately to decrease the electricity not-satisfied by 40%. The last chart could be the most interesting option, in terms of electricity exploitation, since increasing the power installed only 25%, the electricity not-satisfied can be reduced by 75%.

This could be explained by the fact that the solar plant works only 6 h, most of the time is running when the sun is out. This means that the exploitation of the solar plant could have a higher efficiency with this operation time. Nevertheless, since an assessment of the performance and economic will be carried out with all scenarios, it has decided to choose the best power for each operation time, being 30 MW for 24 h, 55 MW for 12 h and 85 MW for 6 h, as can be seen in Figure 4.

4.2. Electricity generation

The performance of the solar plant electricity production depends on the power installed and how this electricity can be used to supply the energy to the electrowinning plant. Once the irradiance has been calculated for the specific location and the power selected for the different operation times, it is necessary to know the specifications of the solar panels to install. For this analysis, solar panels from a local supplier were chosen, with the details summarised in Table 1, and the electricity generated per hour calculated with equation 2.

Table 1. Specifications of the solar panels.

Type	Lifetime	Power	Surface	Efficiency
Monocrystalline	25 years	400 W	2 m^2	21%

$$Electricity\ Generated = Irradiance \times Surface \times Efficiency \quad (2)$$

By cumulating the electricity generated every hour of the year (determined using Equation 2), it is possible to analyse the quantity of energy which can (1) be produced, (2) is self-consumed and (3) the excess electricity. Figure 5 and Table 2 summarise the above data, calculated for the different operation times proposed.

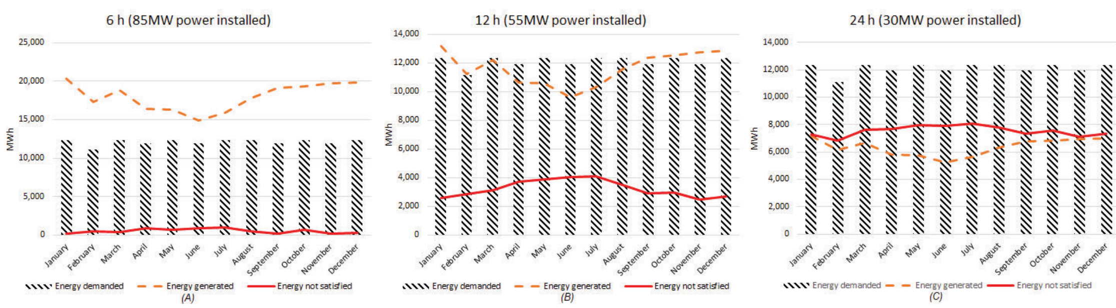

Figure 5. Performance of the solar PV plant designed according to the operation times.

As can be seen in Figure 5, the highest electricity generation (due to solar PV) is produced when the operation time is smaller since the power capacity installed is higher. This makes sense as the higher the power capacity installed, the more panels have been installed and therefore the surface to absorb the irradiance from the sun is larger which translates into higher electricity generation. However, in order to see the performance of the three different operation times, it is important to check how much electricity is not being satisfied by the solar plant. While the demand is constant for the three scenarios, it is shown that the electricity not-satisfied is increasing when the operation time is longer. This is explained by the fact that there is an electricity demand when it is dark with the operation times of 12 h and 24 h. These numbers can be seen in Table 2, where the energy not-satisfied from the total demand is 26.68 % and 62.41 %, for 12 h/day and 24 h/day, respectively. On the other hand, this number drops to less than 5 % when it is operated 6 h/day. Therefore, it is not possible to accomplish these requirements for 12 h/day and 24 h/day with the solar plant alone, so an alternative energy source is required to supplement the electricity demand and keep the electrowinning unit operating.

One of the most important disadvantages of running the electrowinning plant for only 6 h/day is the amount of excess energy generated. Since the plant is only working for 6 h, there are hours during the day that some electricity is being produced and cannot be used, so it would either be (1) wasted, (2) stored in batteries, or (3) sold back to the grid. This is reflected in the self-consumption data being the lowest of the three cases analysed.

Table 2. Annual data calculated according to the solar PV power capacity installed.

https://doi.org/10.52202/069564-0161

Operation time	Power installed	Energy generated	Excess Energy	Self-consumption	Energy not-satisfied	Energy not-satisfied
6 h/day	85 MW	215,845 MWh	77,250 MWh	64.21 %	4.42 %	6,408 MWh
12 h/day	55 MW	139,662 MWh	33,352 MWh	76.12 %	26.68 %	38,690 MWh
24 h/day	30 MW	76,179 MWh	21,670 MWh	71,55 %	62.41 %	90,491 MWh

The following should be noted for the 6 h/day operation. For the combination of solar PV and grid tie backup power, it can be seen from Table 2 that very little energy is needed from the grid (4.42%) to supplement electricity supply and given that excess energy far exceeds the energy not-satisfied (77,250>>6,408 MWh) that the plant is actually likely to be a net provider of electricity to the grid. A Feed in Tariff (FiT) would need to be negotiated with Eskom or the local municipality. There is a similar situation with batteries, as opposed to grid tie, in that excess energy significantly outweighs energy not-satisfied at all times of the year. Therefore, the addition of battery storage capacity should comfortably allow the operation of the electrowinning plant for the 6 hour/day operational schedule. Unfortunately, as there is no tie to the grid, the excess energy which does not need to be stored will be wasted unless an alternative use can be found. It is recommended that further studies investigate lowering the power capacity installed (<85 MW) and increase battery capacity to minimise energy losses. Finally, with respect to solar only (no batteries and no grid tie) unfortunately at this specific power capacity it is unable to entirely meet demand. This is evident by the fact that there is a % of energy not-satisfied. The only way to still meet the annual demand for zinc is firstly to increase the power capacity of the plant ensure the total energy is always satisfied, however this will increase the excess energy which is wasted. The other alternative is to increase the capacity of the electrowinning unit such that during the middle of the day the throughput can be increased to compensate for lower throughput at the beginning and end of the day. However, the economic feasibility of this trade-off would need to be explored in a further study.

The following should be noted for the 12 h/day operation. For the combination of solar PV and grid tie backup power, it can be seen from Table 2 that the energy not-satisfied is fairly significant at 26.68% and electricity from the grid is therefore essential to maintain operations. In addition, as the energy not-satisfied is similar, although still slightly larger than the excess energy (38,690>33,352 MWh), the plant will be a net importer of electricity from the grid. A negotiated FiT is still encouraged to minimise the expense of buying energy from the grid. When using batteries as a storage capacity it can be seen that there is insufficient excess energy generated to be able to be stored and resupplied by the batteries to the plant. The power capacity of the solar plant would need to be increased (at least by 3 MW) above the proposed 55 MW and would also need to account for losses involved in storing the DC energy in the DC batteries. Luckily the high losses associated with DC/AC conversion can be avoided in this process. A solar only supply is unfeasible as can be seen by the aforementioned 26.68%.

The following should be noted for the 24 h/day operation. For the combination of solar PV and grid tie backup power, it can be seen from Table 3 that the energy not-satisfied is high at 62.41% and significantly greater than the excess energy (90,491>>21,670 MWh) meaning that once again the plant is a net importer of electricity from the grid. At the current power capacity of 30 MW, the battery scenario is therefore unfeasible and would require at least an additional 30 MW of capacity to generate sufficient electricity to charge at the batteries. Once again, the scenario with a stand-alone solar operation is unfeasible due to the large amount of energy not-satisfied within the system.

Table 3. Summary of the technical feasibility of the various scenarios under the current constraints**.**

	Electrowinning operating hours and solar PV power capacity (if applicable)		
	6 h/day (85MW)	12 h/day (55 MW)	24 h/day (30 MW)
Grid Only	N/A	N/A	✔
Grid + Solar	✔	✔	✔
Solar + Batteries	✔	?	X
Solar Only	?	N/A	N/A

N/A= not applicable / scenario not investigated; ✓ = technically feasible; ? = not technically feasible under the current conditions, however, requires further investigation as technical feasibility was borderline; X = not technically feasible under the current conditions.

4.3. Key assumptions and limitations of the study

The following key assumptions have been made during this investigation. The plant operates for 365 days a year with no down time and the effect of loadshedding is not taken into account. Electricity use within the zinc plant, other than electrowinning, is not included. The cost of electricity was assumed to stay constant throughout the day and year. A 25-year lifespan was assumed for all economic calculations. Lastly, it is assumed that the quality of zinc will be unaffected if the electrowinning unit runs for only 12 h/day or 6 h/day. It is acknowledged that if some of the above parameters were altered the results may be affected and that further investigations with sensitivity analyses are needed to determine the effect that each assumption has on the results.

5. Economic assessment

The aim of this study is to determine the most economically feasible option(s) of the aforementioned scenarios. To be able to implement an economic assessment, certain factors must be included, such as the price of solar panels and batteries, the capital cost of an electrowinning unit at different scales, electricity price from the grid, price for the compensation of extra energy being fed back into the grid (Feed in Tariff) etc. In addition, the methodology of Levelized Cost of Energy (LCOE) has been applied. This methodology was applied in order to obtain a value to measure the average cost of generating one kilowatt hour (Megawatt hour in this case, MWh) of electricity over the lifetime of a generating asset. The LCOE takes into account the costs associated with a system, including installation, operation, maintenance, and fuel. The average cost per year (over 25 years) has also been determined in Table 5 to provide the easiest comparison amongst the scenarios.

As obtaining electricity solely from the grid has been deemed the benchmark, this value will be calculated first. It must be noted that the price for the power supplied from the grid (Eskom) is assumed to remain constant (no peak hour costs), even though it varies in quantity amongst the different operating times. Based on this, it has been calculated that the electricity cost (OPEX) associated with obtaining electricity solely from the grid is $ 10,585,000 ($ 10.585 M) for the 2022/2023 year. Further Eskom electricity price increases are expected as outlined in Table 4.

The capital cost of the zinc electrowinning unit was estimated using capital cost data from a copper electrowinning unit [45]. The CAPEX for the solar PV plant was taken as the 2021 worldwide estimate for solar installations which is $ 857 per kW [46] which was comparable to the $/kWh value quoted by Green Pro Consulting of $ 778/kWh [47]. The prices applied to the various scenarios, are summarised in Table 4.

Table 4. Costs associated with the various solar PV plant designs.

Price of grid (Eskom) supplied electricity [39]	FiT (based on CoCT) [48]	CAPEX associated with different scales of the Electrowinning Unit			CAPEX for Solar PV plant [46]	CAPEX for battery storage (Lithium)
		6 h/day (85 MW)	12 h/day (55 MW)	24 h/day (30 MW)		
$ 73 / MWh*	$ 18 / MWh	$ 150 M	$ 75 M	$ 35 M	$ 857,000 / MW	1,005 $/kWh

The final LCOE price is determined by the power installed, as the more power installed the more panels are needed. Accordingly, it is also necessary to include the operation and maintenance (O&M) costs, which is usually calculated as the 10% per year of the capital cost. Using these values and the LCOE method, to calculate the feasibility of the design for a 25 years of lifespan, it has been calculated that the LCOE price for the 6 h/day, 12 h/day and 24 h/day are $ 80.66 /MWh, $ 65.77 /MWh and $ 57.87 /MWh, respectively (without taking into account the batteries). Although the price calculated for the 6 h/day scenario is higher than the price from the grid in 2022, it should be noted that once the proposed 18% price increase takes effect, all scenarios will be cheaper ($/MWh) than the grid-only price. In addition, having the embedded generation capacity (through solar PV) provides additional advantages compared with solely relying on the grid connection for electricity supply. As discussed in the introduction, as South Africa continues to experience load-shedding it results in interrupted power supply on almost a daily basis which is affecting the production of all industries including mining and refining of metals. Having an independent embedded electricity generation capacity will therefore reduce / eliminate this situation while also having the advantage of decreasing the pressure on the national grid. If excess “green” electricity can be returned to the grid it will also have an added benefit to the stabilising of the grid as well as contributing to meeting renewable energy targets.

Table 5. Summary of the average total cost per year (25 years) for the various scenarios [million $/year].

	Electrowinning operating hours and solar PV power capacity (if applicable)		
	6 h/day (85MW)	12 h/day (55 MW)	24 h/day (30 MW)
Grid Only	N/A	N/A	10.59
Grid + Solar	13.79	10.38	9.79
Solar + Batteries	1,045	6,230	14,555
Solar Only	14.79	N/A	N/A

https://doi.org/10.52202/069564-0161

The most economical configuration is therefore operating a solar plant for 24 h/day with a combination of grid and solar energy supply. It should be noted that the grid only price of $ 10.59 million/year is expected to increase to $ 12.47 million/year in 2023/2024 as an 18% increase is expected and to $14.07 million/year by 2025 when a further 12% increase is expected. The Eskom supplied electricity cost is expected to continue to increase. With this understanding one can see that all solar and grid options will become more economical than only being supplied by the grid over the 25-year life of the project. With respect to different operating times, the grid and solar option at longer operating times makes more economic sense as it requires less additional capital expenditure in the form of additional electrowinning capacity and additional solar capacity. As can be seen, under no circumstances is the scenario of solar and batteries economically feasible. However, in this scenario it can be seen that, as expected, shorter operating times results in a smaller capital cost (less batteries required) and thus is more economical than longer operating times. Lastly, the reason the solar and grid combination for 6 h/day is more economical than solar stand alone is the benefit gained from selling electricity back to the grid.

6. Conclusions

A stable (and economical) electricity supply is one of the key necessities that society (households and companies) requires. Unfortunately, there are a number of factors which are generating volatility in terms of the supply and cost of electricity. Globally, a major factor in the increasing price of electricity is the Russian-Ukrainian war, with some European countries experiencing an increase of up to 200%, while on a local scale South Africa is struggling with insufficient generation capacity, ageing infrastructure amongst other factors. The hope is that globally and at the local level, these challenges will promote the implementation of increasing quantities of alternative (renewable) energy sources to alleviate dependence on fossil fuels and or countries' national energy grids.

Different scenarios were analysed to determine the optimal incorporation of solar PV for the electricity substitution for zinc electrowinning, namely: grid only, solar and grid supply, solar and battery storage, and a stand-alone solar supply. Although the ideal would be to maximise reliance on embedded generation capacity, it needed to be determined as to where this optimal point currently is. It should be acknowledged that this optimal may change over time. In addition, the operational times were varied (24h, 12h and 6h) in order to determine the trade-off between increased capital costs associated with increasing the size of electrowinning units and solar plant power capacity as the operational time decreased) and the increased costs of energy storage (as operational timeless increased). Accordingly, it has been demonstrated that the best orientation for the solar panel is facing South with a slope of 30º, obtaining the highest electricity production within a year, and ensuring similar monthly generation.

With this configuration, the most promising scenario to maximise reliance on embedded energy generation, is running the electrowinning plant for 6 hours per day. The reason being that it had the lowest energy not-satisfied (< 5% of the total electricity demanded in a year), while the 12 h and 24 h scenarios resulted in 27% and 64% energy not-satisfied. In addition, since the power installed in 6h case is higher than the other scenarios, there will also be excess energy that can be introduced into the grid which may assist in stabilising the grid while the company owning the zinc plant may derive economic benefit. While the 6 h/day solar can feasibly be combined with a grid or battery supply to cover the energy not-satisfied, under the current solar power capacity of 85 MW, running on a stand-alone solar PV plant (no batteries) is not feasible. The power capacity of the solar PV plant would either need to be increased or there would need to be an increase in the capacity of the electrowinning plant to allow for a higher throughput during peak irradiation hours.

The most economical configuration is operating a solar plant for 24 h/day with a combination of grid and solar energy supply. Further studies should investigate how varying only the size of the solar plant will affect the economics in this scenario. Under no circumstances was the solar and battery scenarios economically feasible with the current price of lithium batteries. Future studies should explore alternative energy store options.

One of the main disadvantages of installing solar plants is the amount of land that is needed to produce the electricity expected. For the best-case scenario (6 h/day), from an energy generation perspective, the land use would be 0.425 km2, taken into account only the panels. This number can increase from 30-50%, up to 0.64 km2 after adding the separation between panels and rest of equipment. Choosing the option of installing the lowest number of panels (30 MW plant operating for 24 h/day), the land use can still be in excess of 0.25 km2, which is still significant. However, compared to the existing 46 MW solar PV plant in Aggeneys, which is 110 hectares (1.1 km2) the proposed land area per MW installed is significantly less. In addition, Aggeneys as a town not pressurised for space (i.e., it is not densely populated), therefore the space requirements are not anticipated to be problematic.

One benefit from this study is that the approach can be applied to similar industries/unit operations where the electricity is needed in direct current form, which avoids additional losses incurred when converting from DC to AC and vice versa. For instance, it could be applied to electrowinning plants for other metals located in other areas such as Europe. Other locations may have advantages or face different challenges, for instance in

Europe although there are established FiT schemes, the solar irradiance is significantly lower and there may be more space constraints.

This study has demonstrated that the incorporation of solar PV into the energy supply mix for a zinc electrowinning plant can be beneficial. To that end, governments such as South African government must incentivize the continued investigation and investment into solar PV and other renewable energy sources which can improve the energy stability of the country as well as meet the increasing worldwide expectations on decarbonation within the minerals and metals industry.

Acknowledgement

This paper has received funding from a European Commission project called Treasure, with Gran Agreement Number: 101003587.

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