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UNIVERSITY OF CAPE TOWN

Solar Energy in the Minerals Processing
Industry: Identifying the first opportunities

By

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ABSTRACT

Solar energy, particularly electricity generated from the solar resource, has long been thought to be amongst the most expensive energy products. However, in a climate of electricity shortages and pressures on industries to reduce energy-related greenhouse gas emissions, many previous truths are being challenged. In the solar energy field there have emerged several technical and market innovations, thus making it more attractive. This could be of interest to many mining operations which are located in desert-type environments with high solar insolation and far from electricity grids.

The objective of this dissertation is to evaluate the use of the available solar energy technologies at utility scale to supply the high energy demand of selected minerals processing industries by co-locating a solar power plant with a minerals processing operation. The effect on how the use of a utility scale solar energy use affects fuel transportation energy and conversion and transmission line losses is assessed.

The study analyses the energy usage of different typical minerals processing operations, to identify the processing areas that are likely to benefit from the use of solar energy. Comminution, hot leaching processes and electrowinning circuits are shown to be the most energy intensive areas. Comminution requires high voltage AC power which can be supplied by the solar thermal (ST) technology which converts solar heat to steam which then drives a turbine. Process steam generation can also be achieved directly from ST technology. Electrowinning on the other hand requires low voltage DC electrical output, which can be generated directly using Photovoltaic (PV) technology.

Five minerals processing operations, chosen to represent a range of different types of processes and energy supply scenarios, are profiled and their energy requirements quantified as a basis for establishing the extent to which solar energy can augment energy supply in different cases in this industry.

A qualitative analysis shows that CSP is the preferred option for operations that have mainly an AC load but the unavailability of water in most desert-type locations makes CSP unattractive. Such operations include the Etango Uranium mine in Namibia, which relies on diesel generators for power supply, and the concentrators at the Escondida copper mine in Chile, which rely on long distance grid extension for power access.

For operations that have both an AC and DC load along with thermal demands, both CSP and PV are shown to have advantages and therefore the qualitative analysis was inconclusive. These included Skorpion Zinc, Escondida copper and Rustenberg base metals refineries. The PV option was explored further, with a detailed study conducted for the Skorpion zinc operation. This was achieved by considering different scenarios of using solar energy in this remotely located metals refinery and comparing them with the current mode of electricity supply and its losses. These were quantitatively estimated for line losses, conversion losses and fuel consumption due to inefficiencies.

The scenarios studied for the Skorpion Zinc Refinery in Namibia were: A base case scenario for the current mode of electricity supply and a renewable case which included two different sub-scenarios, i.e. Co-locating a solar power plant with the refinery and a stand-alone case where a solar power plant is located on a site in the same region but with a better solar radiation than at Skorpion Zinc. The findings of this study suggest that remote operations with a high DC electrical input load would benefit from co-locating a utility scale solar photovoltaic power plant with their operation. Co-location reduces annual transmission line losses by 40 % and conversion losses by 24 % from the base case, whereas in the case of a stand-alone solar power plant transmission losses are only reduced by 7% with a 28.5 % increase in conversion losses.

It is concluded that:

For a new operation that is grid remote, co-location of a hybrid solar-diesel power plant reduces fuel losses and could be an eco-efficient alternative to grid extension;

If there is an existing grid, co-locating a minerals processing plant with a solar thermal power plant would benefit operations with a high AC load;

On the other hand, for mining operations where there is a high DC load, co-locating a solar photovoltaic power plant would result in avoided electrical losses associated both with transmission and with AC-DC conversion.

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DEDICATION

For MmaChiloane, Patmore, Gwendolene, Mmasetšhaba and Reneilwe.
Your vital support and patience throughout my studies have made me what I am today.

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NOMENCLATURE

Band gap - the energy difference (in electron volts) between the top of the valence band and the bottom of the conduction band in insulators and semiconductors.

Base metal - a term base informally used to refer to a metal that oxidizes or corrodes relatively easily, and reacts variably with diluted hydrochloric acid (HCl) to form hydrogen. Examples include iron, nickel, lead and zinc. Copper is considered a base metal as it oxidizes relatively easily, although it does not react with HCl.

Beneficiation - a variety of processes whereby extracted ore from mining is separated into mineral and gangue, the former suitable for further processing or direct use.

Comminution - the process in which solid materials are reduced in size, encompassing crushing, grinding and other techniques

Conductor: A combination of wires not insulated from each other suitable for carrying an electric current

Electrowinning - also called electroextraction, is the electrodeposition of metals from their ores that have been put in solution or liquefied.

Energy density - the amount of energy stored in a given system or region of space per unit volume.

ESKOM - a South African electricity public utility, it is the largest producer of electricity in Africa, is among the top seven utilities in the world in terms of generation capacity and among the top nine in terms of sales.

Fossil fuels - fuels which are formed by natural resources over millions of years, sometimes exceeding 650 million years. They contain a high percentage of carbon, and include coal, petroleum, and natural gas.

Hybrid - Hybrid solar power systems most commonly take the form of solar power systems combined with other sources of energy as a form of backup power.

Hydrometallurgy – a part of the field of extractive metallurgy involving the use of aqueous chemistry for the recovery of metals from ores, concentrates, and recycled or residual materials

Insolation - measure of solar radiation energy received on a given surface area in a given time.

Inverter - an electrical device that converts direct current (DC) to alternating current (AC); the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits.

Irradiation - process by which an item is exposed to radiation.

Load - If an electric circuit has a well-defined output terminal, the circuit connected to this terminal is the load. It may also refer to the power consumed by a circuit.

Maximum Power Point Tracker - is a high efficiency DC to DC converter that presents an optimal electrical load to a solar panel or array and produces a voltage suitable for the load.

NamPower - the national power utility company of Namibia.

Ore - a type of rock that contains minerals with important elements including metals. The ores are extracted through mining; these are then refined to extract the valuable element(s).

Ore grade - the grade or concentration of an ore mineral, or metal, as well as its form of occurrence, which directly affect the costs associated with mining the ore.

Precious metal - a rare, naturally occurring metallic chemical element considered to have a high economic value.

Pyrometallurgy - a branch of extractive metallurgy which consists of the thermal treatment of minerals and metallurgical ores and concentrates to bring about physical and chemical transformations in the materials to enable recovery of valuable metals. It may produce saleable products such as pure metals, intermediate compounds or alloys, suitable as feed for further processing.

Rectifier - an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which is in only one direction, a process known as rectification.

Renewable energy - energy that can be naturally replenished and comes from natural resources such as sunlight, wind, rain, tides, and geothermal heat.

Solar cell - (also called photovoltaic cell) is a solid state device that converts the energy of sunlight directly into electricity by the photovoltaic effect. Assemblies of cells are used to make solar modules, also known as solar panels. The energy generated from these solar modules, referred to as solar power, is an example of solar energy.

Solar concentrator - device used to optimise the efficiency of solar power by concentrating the sun's rays onto a focal point using a mirror or a Fresnel lens and then spread out into a light spectrum via a prism.

Solar fraction – amount of energy provided by the solar technology divided by the total energy required.

Sustainable development - a pattern of resource use that aims to meet human needs while preserving the environment so that these needs could be met not only in the present, but also for generations to come.

Sustainable energy - the provision of energy that meets the needs of the present without compromising the ability of future generations to meet their needs. Sustainable energy sources are most often regarded as including all renewable sources, such as plant matter, solar power, wind power, wave power, geothermal power and tidal power.

Synergy - two or more agents working together to produce a result not obtainable by any of the agents independently.

Thin film solar cell - is a solar cell that is made by depositing one or more thin layers (thin film) of photovoltaic material on a substrate. The thickness range of such a layer is wide and varies from a few nanometers to tens of micrometers.

White paper - is an authoritative report or guide that is often oriented toward a particular issue or problem.

Working fluid/ Heat transfer fluid - is a pressurised liquid or gas that causes a machine to operate. In a thermodynamic system, the working fluid absorbs or transmits energy.

ABBREVIATIONS

AC	Alternate current
BMR	Base Metals Refinery
CIS	Copper Indium Diselenide
CO ₂ eq	Carbon dioxide equivalent
CRS	Central Receiver Systems
CSP	Concentrated Solar Power
DC	Direct current
DCS	Distributed Receiver Systems
DNI	Direct Normal Irradiation (Used for solar thermal applications)
GHG	Greenhouse Gas
IR	Infra Red
LEC	Levelised Cost of Electricity
LTl	Latitude Tilt Irradiation (Used for photovoltaic applications)
MC plant	Magnetic Concentrator plant
MMC	Manganese Metal Company
MME	Ministry of Mines and Energy in Namibia
MPPT	Maximum Power Point Tracker
PMR	Precious Metals Refinery
PV	Photovoltaic
RBMR	Rustenburg Base Metals Refinery
REFIT	Renewable Energy Feed-In Tariff
ROM	Run Off Mine
SING	Sistema Interconectado del Norte Grande (a Spanish acronym, which refers to the northern grid in Chile).
ST	Solar Thermal
STPP	Solar Thermal Power Plant
UV	Ultra Violet

Chapter 1 INTRODUCTION

The minerals processing industry uses energy intensive processes that often depend on a steady supply of electricity for smooth day to day operation. In many cases, fossil based fuels are used to generate this electricity and these fuels are known to have detrimental effects on the environment. On the other hand, remote mining sites may incur significant costs for transport of fuel for onsite electricity generation, or for extension of the electric grid. In some cases, these sites are in desert-type locations where they experience high solar radiation and high insolation levels. These have an opportunity to use the sun as an abundant, free and permanent resource. This dissertation investigates some of the technologies that are increasingly being used to harness the sun's energy, with a view to matching them up with the energy demands within the minerals processing industry. This first Chapter outlines the background of this study and addresses the context in which it is carried out, stating also the problem, objectives and questions that are of interest. In conclusion to this Chapter, the scope of this study is outlined along with the structure of the whole dissertation.

1.1 Background

Solar energy, in particular electricity generated from the sun as a resource, has long been considered to be among the most expensive energy products. Therefore in the past, the energy potential of the sun was not harnessed since the efficiency and cost of harnessing solar energy did not make it viable financially. The technologies currently involved in harnessing solar energy have evolved from what was available in the past. Current technologies allow the construction of utility scale, highly efficient and cost effective systems. Therefore, in the climate of electricity shortages and pressures to reduce energy related emissions of greenhouse gases, governments are stimulating and industries are opting for renewable energy sources that are not associated with these emissions.

Within the field of solar energy, there are technical and market innovations that have emerged over the past and still continue to do so. Such innovations are of interest for mining and minerals processing operations located in remote desert type areas. These locations experience high insolation levels, making them suitable for solar energy use. To date such operations rely on fossil based fuels such as diesel, fuel oil, coal and natural gas to fire their generators or provide process heat. Some of these operations have to extend the electricity grid over long distances. Infrastructure for electricity grid extension over long distances has proven to be both financially and technically challenging. Electrical energy line losses over long distances become amplified, making such operations more energy intensive.

Fossil fuels are exhaustible and their combustion is associated with GHG emissions which cause dramatic and often detrimental changes in global weather patterns (Tamiotti and others, 2009). As the demand for these fuels increase, their supply becomes limited resulting in price increases, political instabilities and uncertain future supply (Fabiani, 2011). The price increases of these fuels have a negative impact on the operations of the minerals processing industry. Alongside the economic downsides of using fossil based fuels, the environmental impact of these fuels is also eminent. At the same time, various forms of solar energy are becoming more affordable (Stromsta, 2009).

The minerals processing industry makes use of two types of minerals beneficiation plant configurations: stand-alone concentrators supplying stand-alone refineries, and combined concentrator-refinery sites. Concentrators require significant amounts of energy to grind and refineries more energy to produce. The energy intensity is dependent on the type and grade of ore being processed and the processing route followed. Therefore a typical minerals processing operation requires energy products such as steam and electricity. The electrical input could either be AC or DC depending on the wiring of the appliances and applicability for the process it is required for. The steam

grades required also vary between low, medium and high pressure depending on the use. With the current developments within the field of solar energy, these energy products could possibly be supplied by employing technologies which use the sun as a fuel.

The main technologies involved in producing these energy products involve solar photovoltaics (PV), which generates DC electrical output, and solar thermal which produce mainly AC electrical output and potentially different grades of steam. While the intermittency of the sun has long been viewed as a limitation to exploring possibilities of harnessing the sun's energy, there are technologies available such as thermal and power storage that make the energy products collected during the daylight hours available at times when the sun's energy is not available. Although these components remain to be the most costly for a solar power plant, there are R&D projects that are currently exploring other means of storing the sun's energy at a lower cost (Mills and Morgan, 2007). Such advancements are promising a continuous supply of energy products with very low carbon emissions and thus viewed as environmentally sustainable.

Sustainability in energy supply policy

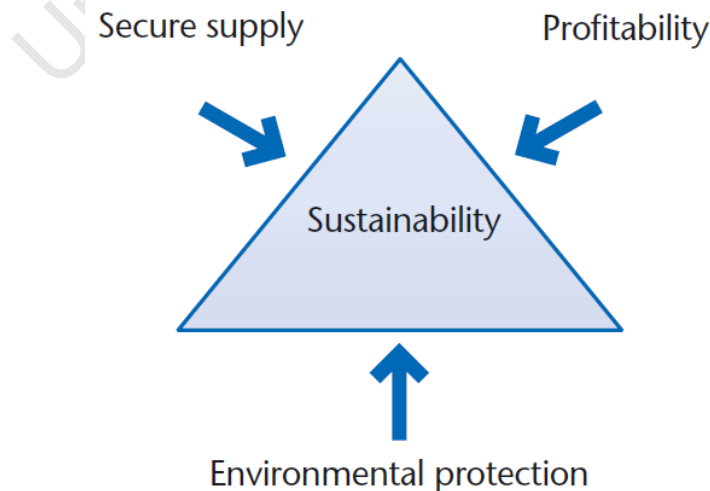


Figure 1: Triangle of goals in energy policy (Schott, 2006)

Schott (2006) has argued, as shown in Figure 1, that secure supply, profitability and environmental protection form the 3 main aspects of sustainability in energy supply. Introducing solar power into the electricity market therefore requires certain requisites in order to become attractive to investors. According to (Schott, 2006) the projects must offer:

1. An acceptable technology
2. An acceptable profit
3. An acceptable financial risk

1.2 Motivation for research

This study was motivated by the imminence of the global climate crisis, by the need to explore renewable fuels and by the observation that end-use energy products from the sun, such as electricity and steam, are for the first time being generated at a utility scale. With all this in mind, there are currently no published studies about how these solar energy innovations can be used for the energy intensive minerals processing industry. The motivation for this study has been summarized as:

- i. Minerals processing industries are aware of their energy-related CO₂ emissions and are actively trying to reduce those (ICMM,2012)
- ii. The global climate crisis is imminent and the use of fossil fuels, which are limited, has driven scientific interest, engineering achievements, commercial interest and policy reform for the development and exploitation of renewable fuels.
- iii. Direct electricity and other end use energy products such as steam are being generated from the sun at a utility scale for the first time (Appleyard, 2009)

1.3 Context of this research study

This study forms part of the Minerals to Metals initiative established in 2006 at the University of Cape Town in the Department of Chemical Engineering. The initiative was motivated by the realisation that making the mineral beneficiation activities means that

the selection, design and operation of minerals to metals processes and technology options must take place within the context of environmental and socio-economic considerations.

One of the objectives of this initiative amongst others is to create a multi-disciplinary centre for carrying out cutting edge research across the field of minerals beneficiation, with a focus on energy, water, benign wastes, and low grade ore bodies. This study is therefore aligned with the objectives of this initiative, and will contribute to the pool of knowledge research that this initiative is collecting for the minerals processing industry.

1.4 Problem statement

The problem statement for this research reads as follows:

Energy intensive operations in the minerals processing industry are highly dependent on fossil based fuels for their electricity and thermal energy demands. This high dependency on fossil based fuels is unsustainable as these fuels are non-renewable. Some of these depend on grid extension for electricity access and those with a DC load have to convert the incoming AC electricity from the grid to DC electrical output. Long distance electricity transmission is associated with transmission line energy losses and AC-DC conversion of electricity results in conversion losses. Among the recent innovations in solar energy, both AC and DC electrical output energy products are being generated at a utility scale.

1.5 Objectives

Based on the problem statement discussed, this dissertation aims to

determine how the use of solar energy at utility scale on the site of a minerals processing industry would first become attractive compared to the fuels that are currently being used to satisfy the energy requirements of this industry. A secondary objective is to quantify environmental gains to be made by such contending solar energy technologies if applied in the minerals industry. This

study will therefore analyse the major energy needs in the minerals processing industry against the background of currently emerging solar energy technologies, climate change mitigation pressures and the quest for sustainable energy supplies.

1.6 Key questions

As fossil based fuels are becoming more expensive than they used to be when they were first discovered, and various forms of solar energy are becoming more affordable, the questions addressed in this study are as follows:

- i. Is there a quantifiable advantage in co-locating a solar energy plant with a mineral processing operation? If so, which factors influence this advantage most?
- ii. In the event that there is a sizeable advantage to such co-location, does the nature of the minerals processing plant influence the choice of solar energy generation technology?

1.7 Approach, scope and limitations

This dissertation focuses on the most energy intensive processes within the minerals processing industry and thus likely to benefit most from the use of solar energy. As there is variation both in the mineral processing industry and in the quality of the solar resource, an approach using multiple case studies is used to describe and evaluate the feasibility of operating a solar power plant at a utility scale on the site of a minerals processing operation.

The information presented in this study is specific to the cases studied. If these studies can be related to other operations of this nature, therefore the findings presented here could be more generally applicable.

Although energy conservation and other ways of minimising energy use in the minerals processing industry would prove to be effective in reducing energy related emissions, it is not within the scope of this study to alter the operations. The main focus of the study is to supplement the energy requirements of the most energy-intensive processes, using solar energy.

In terms of remote mine sites, the scope of this assessment is limited to ore to product processing. The energy requirements associated with mining and product handling are not considered in this study. Only the processes that are identified as being energy intensive are evaluated.

University of Cape Town

1.8 Thesis structure and outline

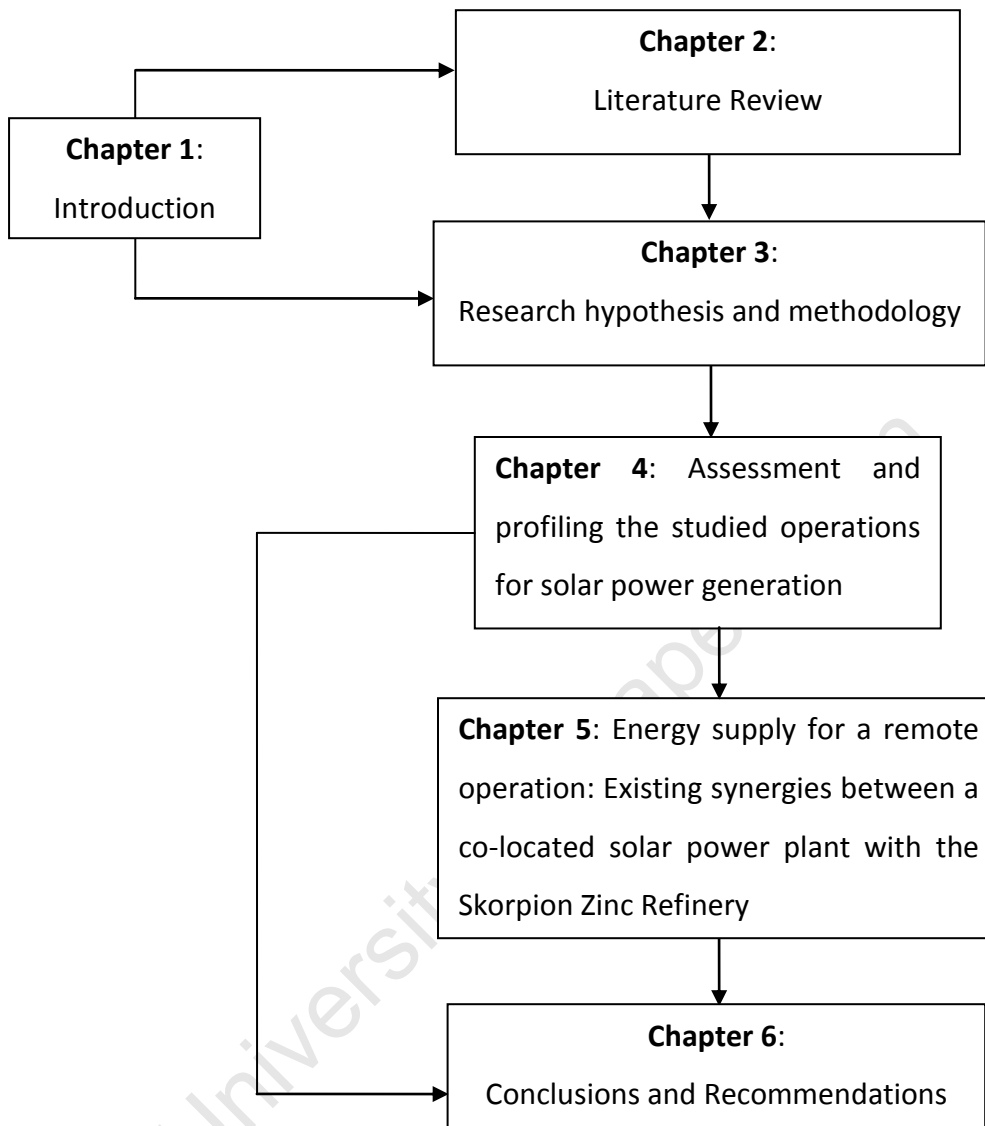


Figure 2: Thesis structure

Figure 2 presents the way this study has been structured. This study has been introduced in Chapter 1, providing a preview of the dissertation. The background is expanded further through a review of the relevant literature in Chapter 2. Chapter 3 builds on this to develop two hypotheses and a methodology for substantiating these. Chapter 4 profiles the studied operations and assesses for each the possible reduction in conventional energy consumption when co-locating a solar power plant with the existing minerals processing operation. Chapter 5 analyses in more detail the possibility

of supplying energy to a remote minerals processing operation, by presenting a hypothetical design of a solar power plant for one minerals processing operation and assessing this by means of a and systems efficiency analysis. The findings made are discussed at the end of each Chapter. Chapter 6 presents the conclusions drawn along with the recommendations.

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Chapter 2 LITERATURE REVIEW

To achieve the objectives of this study as introduced in Chapter 1, it is necessary to review technologies and recent innovations within the field of solar energy, and to contrast these against the energy needs within the minerals processing industry. Ways of reducing energy losses associated with current means of energy supply also need to be considered, including long distance electricity transmission losses, fuel transportation and AC-DC conversion losses.

2.1 Technology assessment: For generating end-use energy products

2.1.1 The sun as an energy resource: Generating end-use energy products

The sun can be used to generate end-use energy products which include both AC and DC electrical output and steam. Solar energy in general has two main disadvantages which affect the production of these energy products. These include the following.

1. Low energy density
2. Intermittency

The first disadvantage leads to low efficiency when producing both AC and DC electrical output. To overcome this disadvantage, the energy density of the solar radiation is increased by optical concentration in the case of producing AC electrical output. The second disadvantage leads to unreliability in energy supply. To overcome this, thermal storage is used in the case of AC electrical output and batteries in the case where DC electrical output is used. The amount of energy received from the sun that reaches the top of the atmosphere is about 1300 W/m^2 (Anthony, Durscher & Remmers, 2007). As solar radiation passes through the outer atmosphere, some this energy is absorbed, reflected, scattered or transmitted and this affects the overall solar input by 30% on a clear day and 90% on a cloudy day. Therefore a maximum solar radiance of 1000 W/m^2 is used to determine the peak rate in solar system designs.

There are different technologies used to generate end-use energy products such as electricity (AC and DC) and steam (different grades). These can be categorised as Photovoltaic (PV) and Solar Thermal (ST) technologies. PV technology uses sunlight directly to produce DC electrical output which can be manipulated via inverters to produce AC electrical output. ST technologies concentrate the sun's rays to a focal point using reflective surfaces increase the energy density and to produce high temperature heat which can be used for steam generation and indirectly using thermodynamic cycles for electricity generation. There are also non-concentrating types of solar collectors known as flat plates, which can produce temperatures of about 100°C or less and are applicable for uses such as building heating and cooling, domestic hot water and industrial process heat (Gordon, 2001). Solar photovoltaic and solar thermal concentrating technologies are discussed in detail in the sections that follow.

2.1.2 Photovoltaics

Photovoltaics (PV) are a solar technology which produces electricity directly from solar radiation using solar cells encapsulated in panels which are made from semi-conductor material. PV uses light from the sun and not heat and high temperatures reduce the efficiency of PV panels, unless the module is fabricated to withstand high temperatures (Ullal & von Roudern, 2007).

2.1.2.1 Typical set-up of a PV solar power plant

A maximum power point tracker (or MPPT) is a high efficiency DC to DC converter that presents an optimal electrical load to a solar panel or array and produces a voltage suitable for the load (Anthony, Durscher & Remmers, 2007). These controllers can increase the output of any solar panel by 15-20 % by trading volts for amps (and vice versa) to adjust the array output to changing conditions (clouds, snow on the ground, the angle of the sun). They also accept high voltage input directly (Chiras, K & R, 2009). The MPPT controller is programmed to the desired voltage for the battery bank to run at, and it automatically adjusts the array. The results are greatly increased output on overcast days and greatly increased output when the sun is not hitting the panels at an

optimum angle. MPPT makes expensive mechanical trackers (Leonics Co, 2009) less and less cost effective. Figure 3 shows how a solar array with an MPPT device is configured.

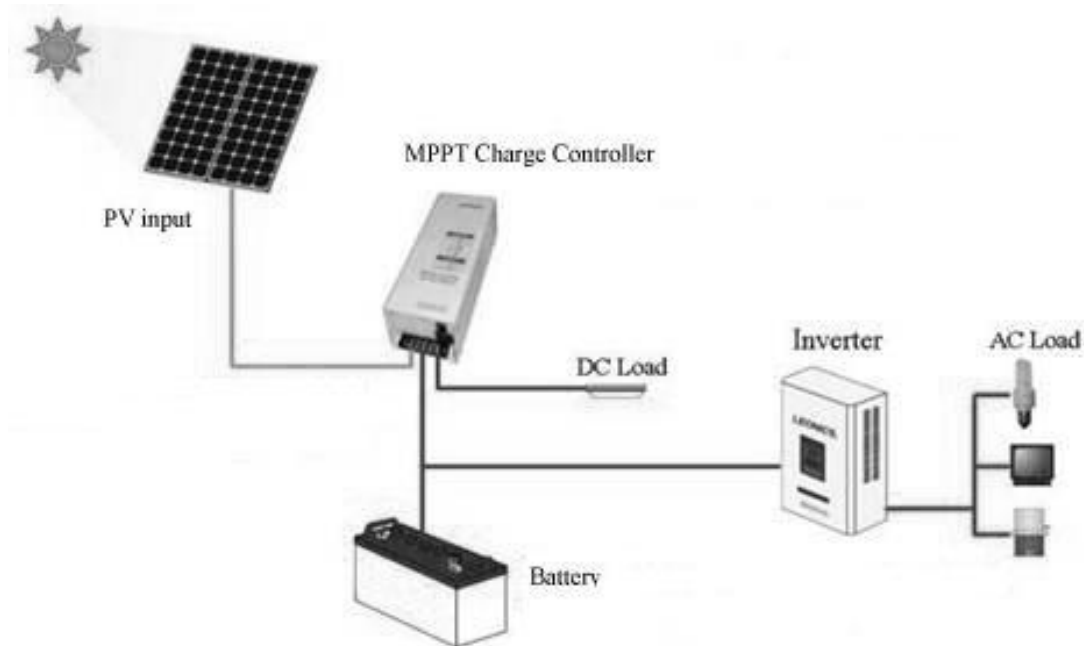


Figure 3: General configuration of a solar array with an MPPT device (Leonics Co, 2009)

2.1.1.1 Semi-conductor materials suitable for PV production

Materials suitable for PV production are determined by their band gaps, which range between 0 and 4 eV for semiconductor materials (Wadia, Alivisatos & Kammen, 2009). Figure 4 shows some of the semiconductor materials that can be used for Photovoltaic applications and their band gaps and maximum efficiency, depending on their temperature and the sun's concentration.

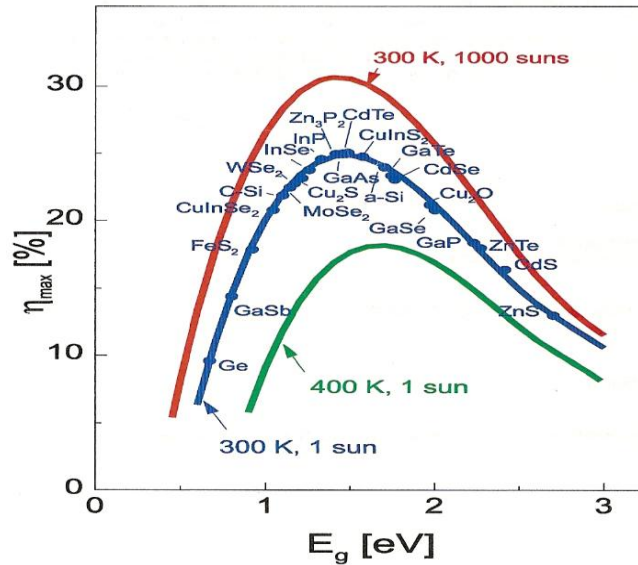


Figure 4: The maximum efficiency vs. band gap for single solar cells for 1 sun at 300K and 400K and 1000 suns at 300K for 23 inorganic PV semiconductors (Wadia, Alivisatos & Kammen, 2009)

Cells can be manufactured using different types of materials but silicon (Si) is by far the most leading, although it is highly energy intensive and costly. Current technologies are comprised of: Crystalline Si dominates the majority of the PV market and accounts for about 93% of the modules for both small scale and utility scale applications. Thin film technology accounts for the remainder; with amorphous silicon (a-Si) at 4.2 %; copper-indium-diselenide (CIS) at 0.7 % and cadmium-telluride (CdTe) at 1% (Anthony, Durscher & Remmers, 2007).

Although silicone(Si) is the most common and popular material used for PV manufacturing, semiconductor materials are not only limited to this naturally occurring compound. Iron pyrite (FeS_2) is significantly more attractive in both cost and availability than all other compounds, whereas several of the leading thin film technologies like CdTe are not able to meet large scale (Wadia, Alivisatos & Kammen, 2009).The materials that are considered to be attractive for large scale PV deployment in the future include FeS_2 , a-Si, Cu_2S and Zn_3P_2 according to their order of highest suitability. Wadia, Alivisatos & Kammen. (2009) also mentions that FeS_2 could achieve between 100 and 1000 times

the global annual electricity consumption as compared to the current dominating crystalline Si technology which is only expected to produce between 0.1 and 1 times. The results of this study bring a promising future for the mining industry because FeS_2 is considered as waste in this industry and its disposal is associated with pollution problems such as acid mine drainage formation.

The technologies currently on the PV market and under research and development are discussed in the next sub-sections.

Monocrystalline silicon: Although these cells have the highest efficiency of all PV technologies, they are not widely used because of their high cost (von Roudern, Zweibel & Ullal, 2005). Perovo solar power station located in Ukraine's Crimea region is currently the world's largest PV plant to date has a generating capacity of 105.56 MW (Cleanenergyproject, 2012). Only 25 % of the cells used are mono crystalline and 75 % is polycrystalline.

Polycrystalline silicon: It is less energy intensive to produce and thus cheaper than the monocrystalline. These cells are commonly used even though they are inferior to monocrystalline; this is because at an efficiency of 20 % and lower cost, they are the preferred alternative in this field (NanoMarkets, 2008).

Thin film: These use less material compared to the conventional crystalline technologies, this implies that less raw material is required for their production. A layer of semiconductor material which is 0.5-2.0 μm thick is deposited as a gas on a less expensive substrate such as glass, ceramic, graphite or plastic (Fang, Wu & Kinnier, 1987). OptiSolar and SunPower are currently constructing 800 MW of solar farms in California (Stromsta, 2009), which could become the world's largest set of grid-tied photovoltaic installations. OptiSolar's 550 MW plant is expected to be online in 2013 and SunPower's 250 MW plant by 2012: both these plants use thin film technology.

Amorphous Silicon (a-Si): These have an atomic structure that is random. The efficiency is typically between 6% and 8 % (Ullal & von Roudern, 2007), which is lower than that of crystalline silicon technologies, and also has a shorter lifespan compared to these. It is suitable for large area application, thus utility scale.

Copper-Indium-diselenide (CIS): It is one of the group of general chalcopyrite compounds containing several elements from groups I, III and VI from the periodic table. These materials have a high optical absorption coefficient and can be mixed with other elements to increase the band gap of the resulting cell, thus increasing cell efficiency (Friedman, 2010). The highest efficiency achieved for these cells under laboratory conditions is 19 % (Ullal & von Roudern, 2007), which is higher than that of crystalline silicon. These cells are not currently used in practice because of the specific production procedures. Practical modules have efficiencies of about 11 % (Anthony, Durscher & Remmers, 2007). Indium based cells are not sustainable for large scale utility production because it is estimated that if all the known indium resources are used to manufacture solar cells, the output would be equivalent to 0.6% of the present electricity generation capacity (von Roudern, Zweibel & Ullal, 2005).

Cadmium-Telluride: These cells have efficiencies of around 10% and are relatively easy to manufacture (Anthony, Durscher & Remmers, 2007) compared to the other thin film technologies. However the perception among the public that CdTe introduces toxic materials to the environment because of the use of Cadmium is the main obstacle to the development of this technology for large utility scale production.

Multijunction: These PV cells consist of multiple films of different semiconductor materials. Each semiconductor type has a characteristic band gap to absorb electromagnetic radiation over a portion of the spectrum (Friedman, 2010). Thus, the cell absorbs most of the solar radiation passing through and converts it into electricity.

This concept results in a single cell having higher efficiency. Most multijunction cells are Gallium based and mostly thin film such as CdTe and CIGS.

Gallium Arsenide: These cells are used for the production of high efficiency solar cells (NanoMarkets, 2008). Used for application in concentrated PV systems and in space applications. These cells have efficiencies in excess of 25 % and can operate high temperatures and are resistant to cosmic radiation. Their efficiency is up to 25 % and 28 % at concentrated solar radiation. Special types have efficiencies over 30 % (Anthony, Durscher & Remmers, 2007). They are now approaching efficiencies of 40% and have the potential to achieve 50% in the near future (Ullal & von Roudern, 2007). Although these cells are highly efficient, their cost is extremely high to be considered for use on earth, however they are extensively used in space programs where reliability is more important than cost.

Organic and hybrid: These solar cells produce electricity from sunlight using a polymer which is easy to fabricate and has low potential for negative impact on the environment in comparison to conventional Si based cells (NanoMarkets, 2008). These cells have efficiencies ranging between 4-8 %. Hybrid cells combine the advantages of both organic and inorganic semiconductors. They have cell efficiencies ranging from 18 to 22 % (Anthony, Durscher & Remmers, 2007). The organic material is mixed with a high electron material (inorganic) to form a photoactive layer. When these two materials are in contact, the power conversion is greater than that of a single material (von Roudern, Zweibel & Ullal, 2005). This technology has potential as a low cost solar PV and could be applicable for large utility scale production. However both these technologies are still under research and development and are not commercially available.

2.1.2.2 Concentrator and hybrid:

The vast majority of solar modules absorb both direct and diffuse radiation and convert it into electricity. However, only direct radiation is captured by concentrating solar

collectors. Concentrating solar collectors are equipped with concentrating lenses or mirrors that focus solar energy onto PV cells to increase their output greatly. Although they are more efficient than standard flat plate modules, they are not common. To reduce the overall cost of solar cells, sunlight is usually concentrated with mirrors or lenses on small cell areas (von Roudern, Zweibel & Ullal, 2005). This reduces the total area of the solar cell required by two orders of magnitude and the efficiency of the cells increases with concentration. The photovoltaic power station proposed for Australia (Mildura/Swan Hill) will use heliostat concentrator technology, and is expected to have a capacity of 154 MW when it is completed in 2013 (Wenzel, 2008).

2.1.2.3 Tracking technology:

These panels track and focus directly on the sun at any point and time. It can either be one axis or two axes. Most solar experts recommend adjustments twice a year: the first at or near the beginning of summer and the second at or near the beginning of winter. According to (Chiras, K & R, 2009) PV modules generate most electricity when they are directly facing the sun. According to Table 1, not much output is lost if the tracker is a little off and does not point the array directly at the sun. The relationship between tracking error and output is the cosine function. The tracking error is the angle between a line perpendicular to the surface of the array and a line from the array to the sun. Table 1 shows the effect that the tracking error has on the PV output. Parameters such as time of the day, season, latitude and climatic conditions are also important in maximising energy capture from the sun using a collector.

Table 1: Effect of tracker error on PV output (Chiras, K & R, 2009)

Tracking error (Degrees)	Relative PV output (%)
0	100
5	99.6
10	98.5
15	96.6

20	94
25	90.6

One of the concerns/myths about PV cells is that it takes more energy to manufacture them than you get out them. The truth is that it does take energy to manufacture PV cells and according to a study by CrystalClear (Sinke, 2005) and further supported by NREL¹ along with (von Roudern, Zweibel & Ullal, 2005) suggest that the energy payback period is as short as one to two years. Given that a PV system will continue to produce electricity for 30 years or more, a PV system's lifetime production will far exceed the energy it took to produce it. These studies suggest that it takes two years for a PV system with Monocrystalline solar cells, 1.7 years for Polycrystalline and 1.5 year for modules made from ribbon polycrystalline system to make as much energy as was required to manufacture the entire PV system. According to the National Renewable Energy Laboratory, thin-film modules which require even less energy to produce, achieve energy payback in one year (von Roudern, Zweibel & Ullal, 2005). These studies were performed in sunlight conditions similar to those found in southern Europe with an average insolation of 4.7 peak sun-hours. For those who live in sunnier climates, the energy payback would be even quicker. For those who live in less sunnier regions, the payback would be slower (Schott, 2006). Another factor is the economy of scale. It is estimated that a production plant should produce at least 100 MW PV power equivalents per annum to be economically viable (Wolrsegger and others, 2007). With the high demand for PV modules, the cost of production is slowly but surely coming down. The demand for PV has been increasing at a rate of 35% (von Roudern, Zweibel & Ullal, 2005) annually, which makes it clear that governments across the world are realising the potential that the sun has in supplying the world's energy demands. More developments with panel lifetimes as high as 25 years, are expected to decrease payback periods further and periods of 1 year payback (Wolrsegger and others, 2007)

1 <http://www.nrel.gov/docs/fy99osti/24619.pdf>

have been reported to date. These low payback periods include environmental and financial benefits with high returns on energy investments and carbon emissions avoidance.

2.1.3 Concentrated solar thermal power

These technologies use optical concentration to increase the energy density of the sun and increase the thermal efficiency in the thermodynamic cycle of the power block. Although the solar radiation is a high quality energy source because of the high temperature and exergy at its source, its power density at the earth's surface makes it difficult to extract work and achieve reasonable temperatures in common working fluid (LeBreux, Lacroix & Lachiver, 2009). Using Solar Thermal Power Plants (STPP) means optical concentration of the sun's energy. In these plants, incident sunrays are tracked by mirrored collectors which concentrate the energy flux towards radiative/convective heat exchanges, called solar receivers, where the energy is transferred to a working thermal fluid/ heat transfer fluid. After energy collection by the solar subsystem, optical concentrator, and solar receiver, the conversion of thermal energy to electricity has similarities with the one from fossil-fueled thermal power plants. Concentrated solar thermal power is used by solar thermal power stations; the concept is similar to that used in conventional power stations, which use heat from burning coal, gas or oil or a nuclear reactor to produce high pressure steam. The steam feeds a steam turbine which is connected to an electric generator (Al-Soud & Hrayshat, 2009). Solar thermal plants use the sun as the fuel but concentrate the sun's rays by means of an optical reflector to a receiver which has a heat transfer fluid (HTF). Recognizing both the environmental and climatic hazards to be faced in the coming decades and the continued depletion of the world's most valuable fossil energy resources, CSP can provide critical solutions to global energy problems within a relatively short time frame and is capable of contributing substantially to carbon dioxide reduction efforts. Of all the renewable technologies available for large-scale power production today and for the next few decades, CSP is one of a few with the potential to make major contributions of clean energy because of its relatively conventional technology. It is easy to scale-up and because of their thermal

nature, each of these technologies can be hybridized i.e. operated with fossil fuel as well as solar energy to ensure continuous energy supply even when the sun is not available (LeBreux, Lacroix & Lachiver, 2009).

Dish Stirling/engine: This technology is the oldest of the solar technologies, dating back to the 1800s when a number of companies demonstrated solar powered steam-Rankine and Stirling-based systems. A parabolic reflector in the shape of a dish is used to focus the sun's rays onto a receiver which has a Stirling engine and is mounted above the dish at its focal point. The dish converts thermal energy to electricity by using a mirror array to focus the sun's rays on the receiver end of a Stirling engine. The internal side of the receiver then heats hydrogen gas, which expands (Mills, 2004). The pressure created by the expanding gas drives a piston, crankshaft, and drive shaft assembly much like those in internal combustion engines but without igniting the gas. The drive shaft turns a small electricity generator. The process requires no water and the engine is emission free. Dish/engine systems are characterized by high efficiency, modularity with each module having a capacity of between 7-25kW (Gordon, 2001), autonomous operation. A peak efficiency of more than 30 % can be achieved. Of all solar technologies, dish/engine systems have demonstrated the highest solar-to-electric conversion efficiency at 29.4%. The modularity of dish/engine systems allows them to be deployed individually for remote applications. Dish/engine systems can also be hybridized with a fossil fuel to provide power when the sun is not available (Mints, 2008). Dish collector systems are the technology of choice for distributed electricity generation, which is in the case of remote power supply, off-grid power and village power supply to mention a few.

Parabolic trough/dish: This technology which is also known as the Distributed Collector System is the only solar thermal technology in the world commercially used for electricity production. In the Californian Mojave Desert nine solar electricity generating systems (SEGS) were built between 1984 and 1991 with a total peak of 354 MWe supplied to the grid. Such collectors may be used for various applications from

refrigeration to industrial process heat to electricity generation. Each solar collector has a linear, parabolic-shaped reflector that focuses the sun's direct beam radiation a linear receiver located at the focus of the parabola. A heat transfer fluid (HTF) is heated up to 400°C and circulates through the receiver and returns to a series of heat exchangers where the fluid is used to generate high pressure superheated steam which is fed to a conventional reheat steam turbine/generator to produce electricity. Spent steam from the turbine is condensed and returned to the heat exchangers via condensate and feed water pumps to be transformed back into steam (Gordon, 2001). Their conversion from solar power to electrical power is 23% efficient (Taggard, 2008b). The solar thermal power plants that were built in California in 1985-1991 (Abengoa Solar, 2008) using parabolic trough technology, 350 MW in total, are still functioning well. After a 15 years period of stagnation, due to a decrease in oil prices and loss of interest in solar energy technologies, CSP-investments are growing fast. In Spain the PS10 solar tower near Sevilla (11 MWe) was connected to the national grid in March, 2007. A PS20 (20 MW) solar tower is under construction on the same site. Near Guadix three (AndaSol 1, 2 and 3) 50 MW parabolic trough plants are under construction. They will be equipped with thermal storage, allowing for 7 hours of power production after sunset. AndaSol 1 was put into operation in November 2008 (Honegger, 2009). The total amount of planned CSP capacity in Spain amounts to 1950 MW. In Boulder City, Nevada, a 64 MW parabolic trough plant started production in 2007 (Taggard, 2008a).

The Central Receiver System: This technology is also called the Tower System. It mainly consists of a tower with a receiver on top and a mirror field surrounding the tower. Each mirror is called a heliostat and has a two-axis drive mechanism and is individually controlled to reflect the direct sunlight to the receiver on the top of the tower. Up to now, the largest CRS plant – Solar One, which operated from 1982 to 1988 in the Californian Mojave Desert, used a water/steam receiver system to generate an electrical output of 10 MWe. These types of concentrating collectors are able to produce temperatures of 2000°C or even higher (Taggard, 2008a). Therefore they can be used to

produce electrical power and as high-temperature furnaces in industrial processes. A receiver at the focal zone absorbs the concentrated radiation, and uses it to heat a heat transfer fluid (HTF). The Rankine cycle is the most common end-use application for this technology but it can also be used for other more efficient cycles such as Brayton/combined cycle as well as high temperature process steam. In more than 15 years of experiments worldwide (Taggard, 2008a), power tower plants have proven to be technically feasible in projects using different heat-transfer media (steam, air, sodium, and molten salts) in the thermal cycle and with different heliostat designs. The conversion of solar energy to electrical power is 23% efficient, which is similar to the parabolic trough. Solar Energy Generating Systems (SEGS) is the largest solar thermal energy generating facility in the world at a capacity of 354 MW (Al-Soud & Hrayshat, 2009). It consists of nine solar power plants in California's Mojave Desert. This solar thermal plant has an electricity production of 11 MWe gross power. Based on the technology of tower and heliostat field, this plant is capable of producing 23 GWh of electricity every year (Yao and others, 2009).

The solar chimney: It has three main components, i.e. a solar collector, a chimney and a turbine and uses the greenhouse effect to heat air under the collector. Less dense air rises up the chimney at the collector centre and drives an electricity-generating turbine. It consists of a circular transparent canopy/roof raised a certain height from the ground, with a chimney or circular tower at its centre. The chimney houses one or more turbo generators located at its base. Radiation from the sun penetrates the collector roof and strikes the ground surface beneath it. The heated ground in turn heats the adjacent air. The warm air underneath the collector flows towards and up into the central chimney to drive the turbo-generators (Pretorius & Kröger, 2009). To date, there is only one operational solar chimney which was built as an experimental plant in Manzanares, Spain with an electrical capacity of 50 kW. It has a solar to electric efficiency of 2 %. It operated between 1981 and 1989 and has since been decommissioned. A 200 MW (e) plant has been proposed for Australia and is expected to be the tallest structure with a

height of 1 km and a diameter of 5km (Mills, 2004). Victorville Solar power generating station is currently in construction: this will be the first commercial utility scale Dish Stirling based technology. Construction started in January 2009 and the plant will be built over a four year period. It will be located in Mojave Desert, in California at a capacity of 500MW using a 20 000 dish array.

Linear Fresnel: According to (Wolrsegger and others, 2007), this technology shows a potential to reach significant market shares in emerging global solar thermal power market. It is similar to that of the parabolic trough but instead of using curved optical surfaces, it uses flat or slightly curved ones arranged in parallel lines and positioned reflect sunlight onto a long receiver with one surface having a Linear Fresnel concentrator (Ford, 2008). This technology is an improvement on the parabolic trough technology and on-going research in this field by the German/Spanish Direct Solar Steam project have predicted a 26% levelised energy cost reduction in comparison to conventional parabolic trough technology (Platzer and others, 2004). Less capital is required for assembly and building the plant, and the components are easy to manufacture. As a result, these plants can be assembled and commissioned in months rather than years, making this technology scalable. It has a low visual impact compared to power towers and wind generators, therefore can be sited close to residential areas (Mills, Morrison & Le Lievre, 2003). Their conversion from solar power to electrical power is 19%. In the USA trough and Fresnel plants are planned with a total capacity of 2500 MW, based on a prototype Linear Fresnel plant that was built in Australia close to Liddell Power Station at 1 MW in 2004 by Austra. Based on this prototype, the same company is currently building a 177 MW plant near San Luis Obispo in California (Ford, 2008), but in January 2009, construction had not started.

The biggest disadvantage of solar electric systems currently is that they are costly relative to conventional electrical systems that are mostly fossil fuel based. With this in mind, it is expensive only if you ignore the environmental costs of conventional power

and the subsidies that these technologies receive from taxpayers (Schott, 2006). There are different factors which affect the competitiveness of solar energy with conventional fuels when producing end-use energy products. Some of these include:

1. An area with lots of sunshine and high electrical rates such as California and Hawaii
2. An area with low sunshine but high electrical rates such as Germany

Financial incentives from local power utilities and the government can also drive the cost down, often making solar electricity cost competitive with conventional sources.

Water consumption is important with CSP technologies because they perform best in desert-type locations where the sun is most intense such as Mojave desert where there is little water available. This is a major issue, both for cooling requirements in the power cycle and regarding cleaning the reflective surfaces.

A preliminary assessment when the water demand for commercial CSP technologies is compared to the amount of water used in typical minerals processing operations shows that the water consumption of such operations would increase significantly with the exception of Dish Stirling technology consumes the least water but this technology is not well established for utility scale power generation. This assessment is presented in Appendix A of this thesis.

2.1.4 Backup for the intermittent sun

Photovoltaic generation can only be operated during the daylight hours when the sun is available and most efficiently on a cloudless day. To ensure a sustainable energy supply, means of backup need to be in place. This section discusses the different modes of backup that can be used to support a utility scale solar PV plant.

Grid connected

Grid connected-battery less

Grid connected PV systems are the most popular solar electric system on the market. They are connected directly to the electricity grid and are sometimes referred to as battery less grid-connected or battery less utility tied systems because they do not employ batteries to store surplus electricity. In these systems, the local electrical distribution (the wires that run by the load) accepts surplus electricity (electricity produced by the PV system in excess of the demand of the load). The utility grid supplies electricity to the load when the PV system is not generating power. In a sense, the utility grid serves as a storage medium. The pros and cons of this system are presented on **Table 2.**

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Table 2: Pros and cons of grid-connected battery less systems (Chiras, K & R, 2009)

Pros	Cons
Simpler than other systems	Vulnerable to grid failure unless a back-up generator or an uninterruptible power supply is installed.
Less expensive	
Less maintenance	
Unlimited supply of electricity ²	
More efficient than battery-based systems	
Unlimited storage of surplus electricity(Unless the grid is down)	
Greener than battery-based systems	

Grid connected systems with battery back-up

Grid-connected systems with battery backup are also known as battery-based utility-tied systems or battery based grid connected systems. These systems ensure continuous supply of electricity. Although they are the same as battery-less grid connected systems, they differ in notable ways. One of the most important differences is the type of inverter used. Another notable difference is that they require a battery bank. The third difference is a meter that allows the operator to monitor the flow of electricity into and out of the battery bank. The fourth is the charge controller. The pros and cons of this system are presented on **Table 3**.

² Unless the grid is down

Table 3: Pros and Cons of a battery-based grid tied system (Chiras, K & R, 2009)

Pros	Cons
Provide a reliable source of electricity	More costly than battery-less grid-connected system
Provide emergency power during a utility outage	Less efficient than battery-less grid connected systems
	Less environmentally friendly than battery-less grid connected systems
	Require more maintenance than battery-less grid connected systems

2.1.4.1 Off-grid systems

Batteries of off-grid systems are designed to operate day in and day out, 365 days a year for up to 10 years. Batteries are connected together to produce the voltage and storage capacity required by a renewable energy system. Systems in off-grid homes and businesses are typically wired to produce 24 or 48 volt DC electricity. The low voltage electricity, however, is converted to AC electricity by the inverter, which also boosts the voltage to the 120 and 240 volts commonly used in businesses and homes. Wiring batteries in series boosts the voltage and wiring in parallel increases the amp-hour storage capacity of the battery bank. The number of amp-hours of electricity of a battery bank can store.

Off-Grid (Stand-alone) Systems

Off grid systems are designed for those who want to supply all their energy demands via solar and any other source. These systems usually involve a combination of solar and wind or some other renewable source. Off-grid systems often require support in the form of fossil based fuels when intermittent renewable energy sources are used.

Gen-sets

Generators can be powered by a fuel which could be: gasoline/petrol, diesel, propane or natural gas. Generators produce AC electricity which travels to the inverter (containing a battery charger) or to a dedicated battery charger. The battery charger contains a step-down transformer that reduces the 120 or 240 volt output of the generator to a voltage slightly higher than the nominal battery voltage which could be 12, 24 or 48 volts. The low voltage AC electricity is then converted to DC electricity by a rectifier, also located in the battery charger. DC electricity is then fed into the batteries. At night, an off-grid PV power system uses batteries to supply its loads. Although the battery pack voltage when fully charged may be close to the PV array's peak power point, this is unlikely to be true at sunrise when the battery is partially discharged. Charging may begin at a voltage considerably below the array peak power point, and a MPPT can resolve this mismatch. Transportation fuel losses occur when the transportation of the fuel used to fire the gen-set is considered.

2.2 Energy demands of the minerals processing industry

Some minerals processing operations have access to the electricity grid and depending on the regulations within the country where they are operating they have rights to obtain power from the national utility supplier. Their connection to the electricity grid could be through either long or short distance. With this in mind there are those which are located in remote areas and do not have access to the grid and have to source their own electricity supply. Although some of these operations have opted for modular fossil generated electricity such as diesel generators, solar energy being modular in some cases also has a potential of being used by these operations.

2.2.1 Processing different metal types

There are different metal types in the minerals processing industry and most of these can be categorised in three groups as: Base metals (Low grade ore), Precious metals (trace grade ore) and ferrous metals (high grade ore) (Habashi, 2002). This categorisation was done based on the fact that the processing routes for these metals

are not the same but when they are grouped, certain similarities in processing routes emerge.

2.2.2 Processing routes and energy requirements

The different processing routes in the minerals processing industry mainly depend on the type of mineral being processed. In some cases, different minerals can be processed together where one mineral type is taken as a product and the others as by-products. This is the case in the processing of base metals where precious metals such as platinum are taken out as the by-products and processed further. The processing routes are also dependent on the grade of ore being processed. These processing routes are the Hydrometallurgical and Pyrometallurgical, and either may or may not be preceded by a physical concentration step. These are discussed below and the major emphasis is on the major energy consuming units for these routes.

2.2.2.1 Physical Beneficiation (usually with size reduction)

Beneficiation and size reduction involves the liberation of mineral ore as a preparation stage before the minerals are processed, although this is not applicable for all cases. This stage involves the crushing and grinding of ore to smaller particle sizes. In some applications, ore has to be milled until is in powdery form before it can be taken through a flotation process to separate it from gangue and tailings. This is a mechanical process and electricity is used to drive the mechanical motors for the mills. The process of milling can be energy intensive for applications where ore has to be ground up to very small particles. that are powdery. Alternate current (AC) electricity is used to supplement the energy requirements of the milling process.

2.2.2.2 Hydrometallurgical processing route

This branch of extractive metallurgy involves the use of an aqueous solution which can either be basic or alkaline depending on the properties of the metal that has to be processed. The solution is used to recover metals from ores, concentrates or residual materials. It involves leaching where the solution is brought into contact with the

material containing the valuable mineral. This could involve in-situ, heap, dump or vat leaching, and depending on the type of leaching low pressure steam could be used. After the metal has been leached from the ore, the resulting solution goes through a solvent extraction process where the metal is extracted from one phase to the other before it is recovered in a saleable form in the Electrowinning circuit. The solvent extraction stage requires both steam and AC electricity while the Electrowinning circuit which requires DC electricity is the most energy intensive process in this route.

2.2.2.3 Pyrometallurgical processing route

This route involves the thermal treatment of minerals and metallurgical ores and concentrates for physical and chemical transformation in the materials to enable the recovery of valuable materials. Energy input is required to sustain the high temperatures at which most of these processes take place. This is usually supplied in the form of fossil fuel combustion, exothermic reaction of the material and/or electrical heat. The most energy intensive processes for this route include; preheating, roasting, smelting and refining. Depending on the application, both a DC or AC arc furnace could be used and coal is currently used for preheating. Plants onsite that are associated with this route include an acid plant, slag treatment plant and in some cases, if pure oxygen is used in the furnace, an air separation plant. All these plants are energy intensive and AC electricity is currently used.

2.2.3 Provision of energy needs in minerals processing

Despite different forms of energy being required in the minerals processing industry, most of these are converted from one form to the other resulting in losses and, in the case of fossil fuels, emissions that are harmful to the environment. Some boilers for steam generation use electricity, others coal and yet others, importantly, generate steam by oxidising sulphide minerals.

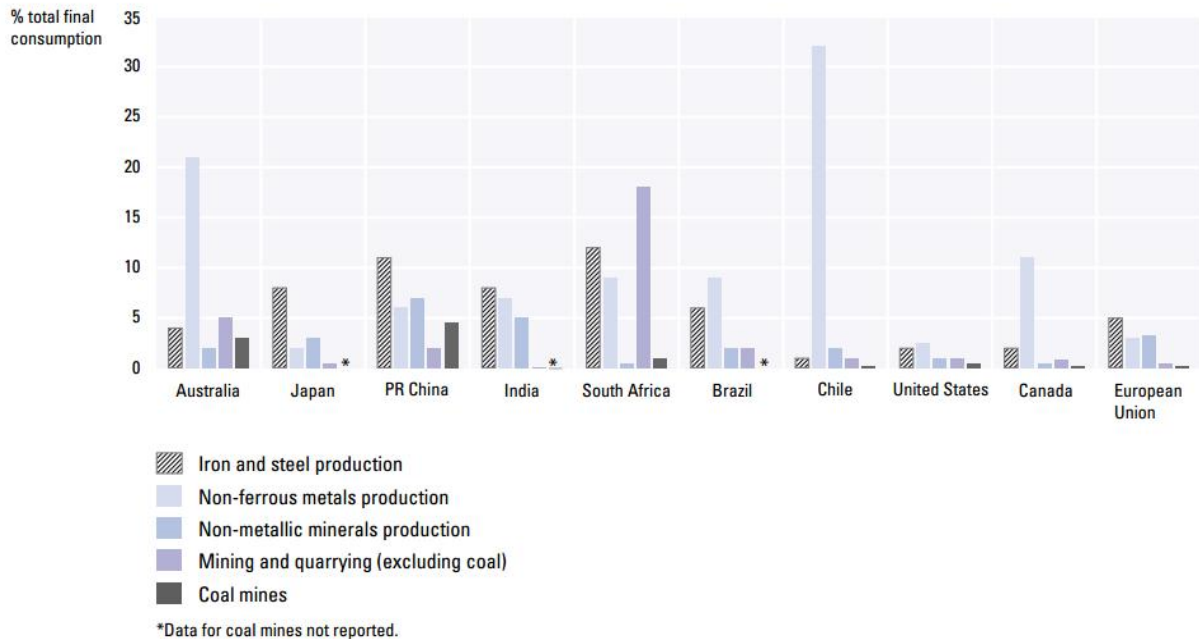


Figure 5: Percentage of Total Electricity Consumption Used by Mining and Minerals Industries, Selected Countries and the European Union, 1998³

Figure 5 illustrates some of the variation among countries in the importance of electricity consumption in different minerals industry sectors. It is clear from this figure that electricity is, of course, only one of many forms of energy used in these industries (MMSD, 2002). The report further states that these minerals industry divisions used 11.3 million tonnes of diesel in 1998 combined, which is only 4% of the total used in road transport (286 million tonnes).

2.3 Transmission system and conversion with rectifiers and inverters

2.3.1 Transmitting power over long distance

When power is transported using transmission networks, there are losses associated with this and a step up transformer which is used to reduce these losses, which increases the costs of erecting such networks. The process of transforming power is usually 99 – 100 % efficient (Bisnath and others, 2005).

³ Sourced from THE MINING, MINERALS AND SUSTAINABLE DEVELOPMENT PROJECT MMSD, pg 252

Factors affecting the performance of a power transmission lines include: Inductance, capacitance, resistance and conductance (Bisnath and others, 2005). These are uniformly distributed along the length of the line⁴. Transmission line losses are usually quantified using the current passed through the line, the resistance and the reactance of the line as demonstrated on the following equation:

$$P_{\text{Loss}} = I^2R + I^2X$$

With R being the resistance of the conductor material used for the transmission line and X being the reactance. The resistance and reactance are dependent on temperature.

Ohm's Law: $V = IR$ and the Power equation: $P = VI$ where used to evaluate the current passing through the voltage lines listed on **Table 4**.

Table 4: Different standard types of voltage transmission lines

<i>Transmission type</i>	<i>Voltage range</i>
Extra High Voltage	above 220 kV
High Voltage	> 132 kV < 220 kV
Medium Voltage	>1 kV ≤ 33 kV
Low Voltage	≤ 1kV

The calculations conducted in this study focus only on the EHV and HV because these are the long distance transmission lines and this study focuses on losses incurred when supplying power to remote locations.

Aluminium Conductors Steel Reinforced (ACSR) is the most common conductor materials used for power transmission. The core of the conductor is steel for reinforcement and the outside bundles are Aluminium for conduction. Aluminum has a low resistance, therefore making it ideal for long distance transmission and reducing transmission line losses. Although steel has a higher resistance, since is it at the core of

⁴ They are reported per km of the transmission line

the conductor cords, its resistance does not affect power transmission (Bakshi & Bakshi, 2009). Although corona line loss contribute to the transmission line losses, these have not been accounted for because they are only significant in wet weather conditions and establishing which part of the long distance transmission line is exposed to rain has proven to be impossible. In dry conditions corona losses can be discounted. Distance of the lines is based on the routing of both transmission and distribution lines. Energy is required for electricity to flow through a resistance which will heat it up.

2.3.1.1 Transmission line losses

Transmission lines that carry power are designed to have a low resistance as possible so they do not heat up. In a transmission line, the wire used has a small level of resistance compared to an electrical heating element which has a high resistance and designed to heat at a very fast rate. Although over a long distance, the transmission heat up and electrical power is lost in this way. Power loss in a transmission line is therefore given by $I^2R + I^2X$ where R is the resistance and X is the reactance of the wires. The transmission line losses increase as the square of the current increase, therefore to reduce the losses, the current should be as small as possible and the voltage as high as possible (Miller & Milinoski, 1994). To minimize the transmission line losses, transmission in the national grid is at high voltages of up to 400 kV and recently with voltages up to 750 kV. To step-down the voltage to a safer level of 240 V and 110V used for most appliances, transformers are used. Alternating current is easier to transform compared to DC and this is the main reason why AC is used in power networks (Smith, 2001). There is a small⁵ power loss each time it is transformed, but this is offset by the advantage in reducing transmission losses. Transmission line losses increase with the length of the transmission line. The distance of the transmission lines has been based on the routing used by the respective utility company. The voltage for each line has also been considered.

⁵ Transformers have been estimated to have an efficiency ranging between 98 and 100 %

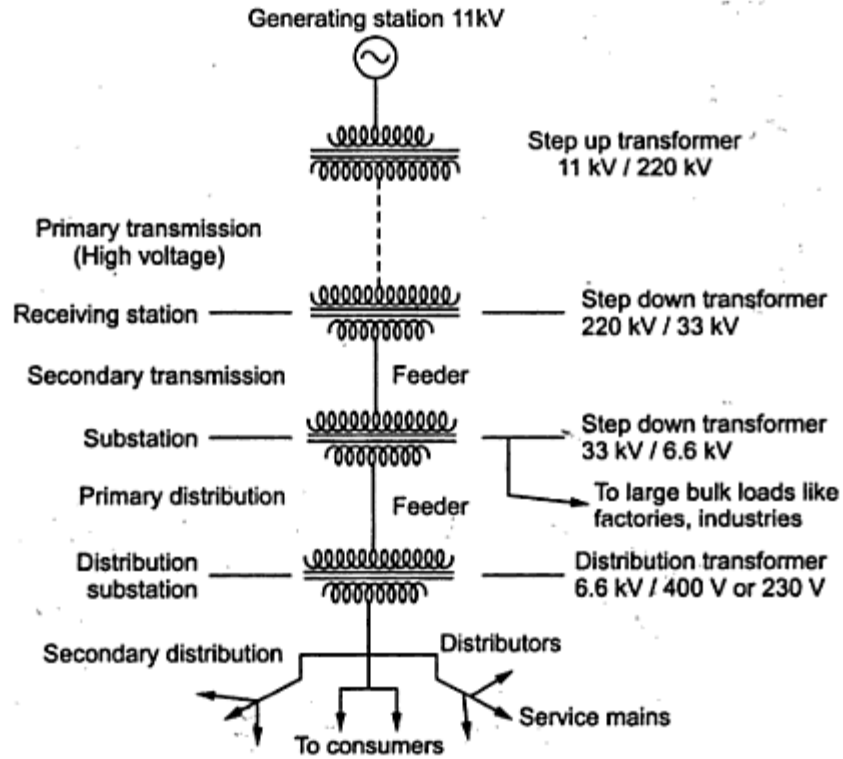


Figure 6: Line diagram of a typical transmission and distribution scheme (Bakshi & Bakshi, 2009)

Power transmission over distances above 100 km uses extra high voltage transmission lines at 400 kV. The line diagram presented on Figure 6 shows the typical scheme used in transmission and distribution.

2.3.2 Conversion from AC to DC and DC to AC electrical output

Industrial applications which require variable DC power include the following:

- Steel mills, paper and textile mills employing DC motor drives
- AC-fed traction system using DC traction motors
- Electro-chemical and electro-metallurgical processes
- Magnet power supplies
- Reactor controls
- Portable hand-tool drives

Before the availability of high power thyristors, Moto-Generator sets, Mercury-arc rectifiers and thyratrons were used to achieve AC to DC conversion. At the moment, thyristor converters which are phase controlled to get variable direct voltage are used to achieve the AC-DC conversion. These phase controlled converters are extensively used in industries (Dubey & Joshni, 1986). When these rectifiers used to convert the conventional AC electricity to DC electricity the associated power losses ranges between 9 to 25 % (Anthony, Durscher & Remmers, 2007) depending on the amount of electricity converted.

The process of rectification produces DC electrical output characterized by pulsating voltages and currents (although still unidirectional) from an AC electrical source. Depending upon the type of end-use, this type of DC current may then be further modified into the type of relatively constant voltage DC characteristically produced by such sources as batteries and solar cells (Dubey and Joshni,1986). A device which performs the opposite function (converting DC to AC electrical output) is known as an inverter.

2.4 Concluding remarks

This Chapter has started by presenting the different technologies and innovations within solar energy. The review of the innovations in solar photovoltaic energy (section 2.1.2) has shown that there has been a significant decrease in the cost of producing solar energy end products and most of these technologies are not as expensive as they used to be due to economies of scale and learning curves. Solar thermal power plants can replace conventional thermal power plants - and without any qualitative change in the grid structure. Due to the option of thermal storage, the turbines of solar thermal power plants can also produce power in low-radiation periods and at night also when combined with conventional thermal power plants. Water usage is a major issue, both for cooling requirements in the power cycle and regarding cleaning the reflective surfaces.

When the sun is not available, back up is required to ensure continuous electricity supply. Grid connected PV systems are the most common solar electric systems. Within grid connected systems, the battery-less systems are seen to be more efficient than battery-based systems. Although systems with a battery-based are a reliable source of electricity and provide emergency power during a utility outage, they remain more costly.

The Chapter then proceeded to analyse energy use in mineral processing and established that typical processing routes are hydrometallurgy and pyrometallurgy which may or may not be preceded by physical concentration. Physical concentration includes crushing and grinding of ore into small powdery particle sizes and AC electricity is used to supplement this energy intensive stage. The plants onsite associated with the pyrometallurgy route are energy intensive and require AC electrical output. The metal rich solution on the hydrometallurgy route goes through solvent extraction before it's recovered in an electrowinning circuit. Solvent extraction stage requires both steam and AC electricity. Electrowinning which requires DC electricity is the most energy intensive. The minerals processing operations⁶ are associated with high electricity and diesel consumption for electricity generation.

The third section of this literature review has focused on losses and inefficiencies associated with current energy usage in the mineral processing industry, particularly for remote operations. Long distance transmission networks present a challenge of intensified transmission line losses; therefore these industries can explore ways of reducing these. Also many of the metals refineries require DC electrical output as their major form of electrical energy, instead of the conventional AC electrical output that is supplied by the electricity grid that they are currently using. These operations thus make

⁶ in all the countries that have high mining and processing activity

use of rectifiers to convert the AC electrical input to DC electrical output which would then be a useable energy product for their processes.

To avoid the identified energy losses, or the need to construct additional grid and conversion infrastructure, the mineral processing industry might be well-placed to take advantage of the solar energy technologies presented in this Chapter.

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Chapter 3 RESEARCH HYPOTHESIS AND METHODOLOGY

This Chapter presents the hypotheses formulated for this study and the methodology used to test the hypotheses.

3.1 Hypotheses

Remote minerals processing operations rely mostly on grid extension to have reliable access to electricity. The electricity supplied via the grid is in AC electrical output and in some cases, these operations require the use of DC electrical output, therefore they need to use rectifiers to convert the AC electricity received into DC electrical output. Grid extension intensifies transmission line losses and the use of rectifiers introduces conversion losses. It stands to reason that such transmission losses could be reduced or possibly avoided if a utility scale solar power plant were co-located with a remote minerals processing operation, and also that the power conversion losses would depend on the nature of power requirements relative to the form in which the power would be generated. This dissertation therefore hypothesizes the following:

- i. The load pattern i.e. the nature of larger power requirements of a minerals processing operation relative to the existing energy infrastructure will dictate how attractive co-located solar energy provision through competing technological options will be.
- ii. A photovoltaic solar power plant co-located with a metals refinery with a high DC load would lead to a significant reduction both in transmission line losses and in DC-AC-DC conversion losses compared to locating PV solar in a location with the best solar resource away from the load. In particular, if a large stand-alone PV plant is considered in the region of such a metals refinery, co-location would more than compensate the difference in the quality of the solar resource through avoided transmission and conversion line losses.

3.2 Methodology

The methodology has been developed to achieve the objectives of this study based on the formulation and testing of the above mentioned hypotheses. The procedure followed in testing the hypotheses is outlined in the figure below.

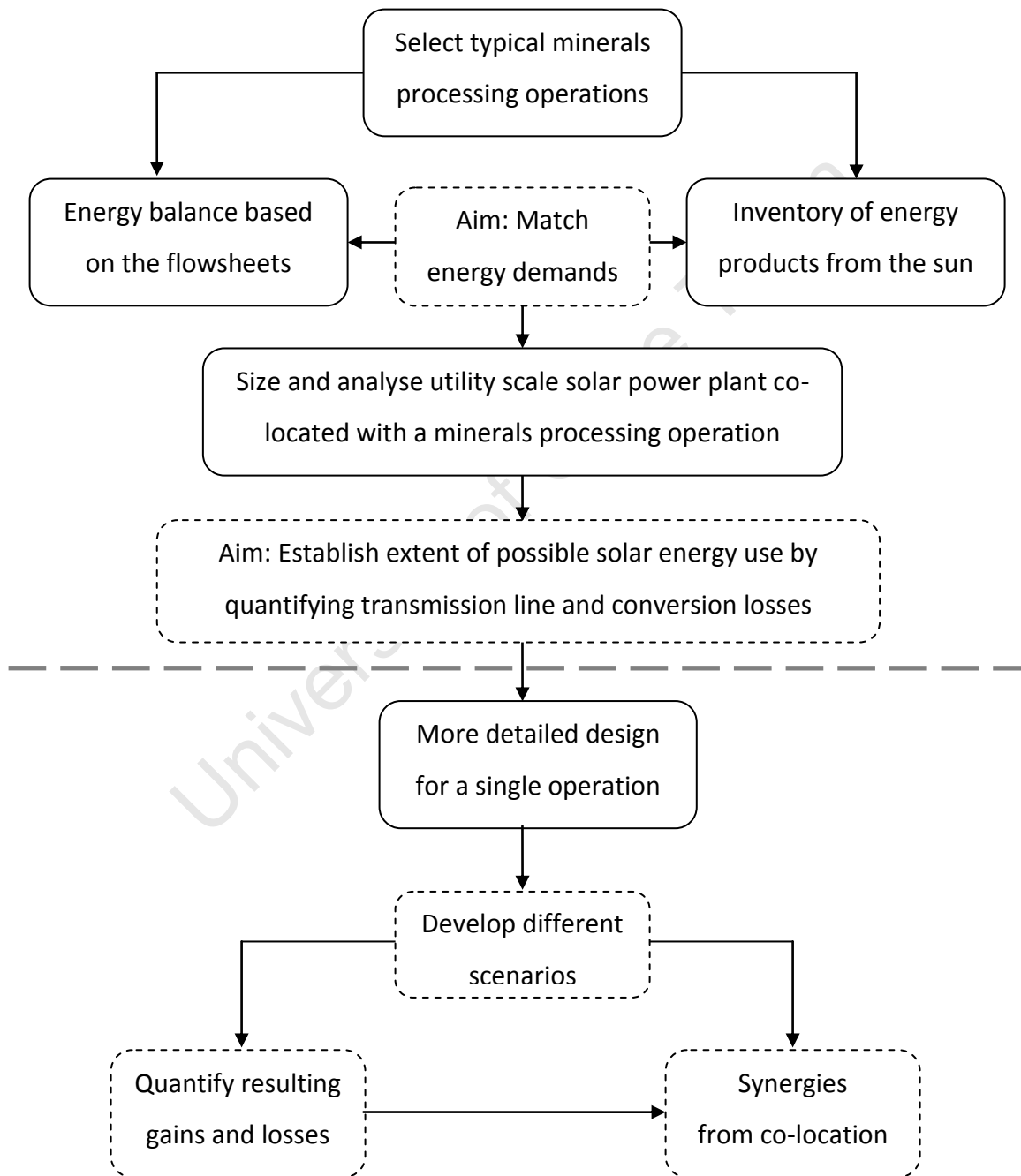


Figure 7: Overview of procedure followed to test hypothesis

As outlined in **Figure 7**, the section above the dashed line is presented in Chapter 4 while the section below the dashed line is presented in Chapter 5. The following steps have been followed in executing this study.

1. Select a range of different typical minerals processing operations
2. Compile an inventory of solar energy products.
3. Conduct an energy balance and audit of the selected operations using the process flowsheet data
4. Match the solar energy products based on the results of step 2 of this process with energy demands of the operations based on step 3 of this process
5. Conduct a qualitative study of the extent to which solar energy can meet the energy demands of the minerals processing industry. This will be done by: Analysing how a utility scale solar power plant co-located with a minerals processing operation would affect the losses that the operation is currently experiencing. These losses will be quantified as: Transmission line losses, AC-DC and DC-AC conversion losses along with fuel consumption losses.
6. Prepare a more detailed hour by hour analysis of one solar plant design matched with one mineral processing operation to investigate the 2nd hypothesis. This will also identify different energy supply scenarios and will be used to quantify and qualify how solar energy at a utility scale can be used and the energy loss reduction that will result from co-location.

3.2.1 Energy needs for types of minerals processing plants

To substantiate the first hypothesis, it is necessary to understand the nature of the larger energy requirements of typical minerals processing plants. As discussed in Chapter 2, it is instructive to divide minerals processing operations into those that process ores where the metal of interest occurs as the majority mineral, a minority

mineral or only in traces. Section 2.3 also provided descriptions of the most commonly encountered energy-intensive operations in minerals processing plants, as illustrated in **Figure 8**.

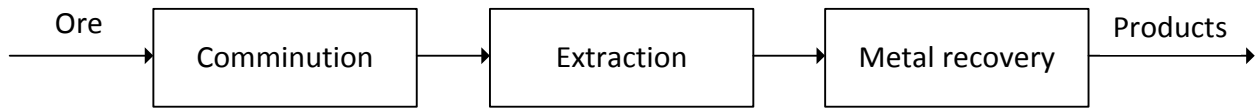


Figure 8: Generalised process flowsheet for minerals processing

3.2.2 Identifying and matching the energy demands of the minerals processing industry with solar energy

The methodology developed in response to the 1st hypothesis consisted firstly of identifying the energy requirements in the three major types of minerals processing industries. Next, these requirements are matched with the end-use energy products from the sun using the available technologies.

Table 5: Typical energy requirements for typical minerals processing operations based on ore grade

		1	2	3
		High grade ore	Low grade ore	Trace grade ore
A	Steam		✓	✓
B	AC electrical power	✓	✓	✓
C	DC electrical power		✓	

Table 5 shows the different ore grades in the minerals processing industry and the typical energy products required to process the ore.

The large majority of mineral processing plants include an energy-intensive comminution step, requiring 3-phase voltage which is supplied from an AC electrical

output. As a result all the different types of ore listed above have the AC electrical power ticked. Typical high grade ore such as ferrous metals are then either sold to smelters or smelted on site, requiring more AC electrical power. In a few cases, a hydrometallurgical process is used needing steam for process heating and DC electrical power for electrowinning.

Low grade ores may either be upgraded by physical separations (e.g. flotation) and then processed, or processed directly (e.g. by heap leaching). Hydrometallurgical technology is more frequently used, requiring process steam and DC electrical power. Some operations which involve low grade ore follow a pyrometallurgical route which would not require DC electrical power. Typical trace grade ore processing requires steam as part of hydrometallurgical installations, and AC electrical power. The product is not always produced in reduced metal form, but there are exceptions where an electrowinning step is included and DC electrical power is required – the energy requirement is however relatively small (esp. relative to the comminution energy requirement) due to the small quantities of metal produced. These energy products can be supplied by solar energy as depicted in Figure 9 below.

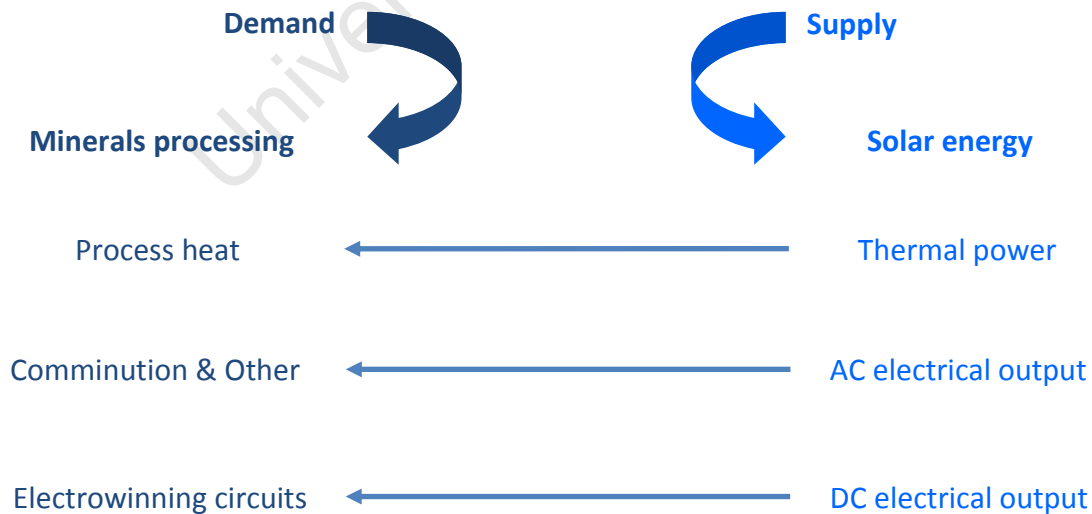


Figure 9: Matching energy demands of the minerals processing industry with energy products from the sun

3.2.3 Qualitative energy analyses

This study focuses on the Minerals Processing industries being studied are located in desert type remote or water-stressed locations. These sites are already water stressed, therefore solar thermal technologies have not been investigated further for either steam or electricity generation since solar thermal technologies require water to be used for cleaning and maintaining the shine of the solar array.

A qualitative analysis of CSP versus PV for co-location with each of the selected cases will be presented. This analysis will further be supported by a quantitative comparison of avoided transmission line losses.

3.2.4 Quantitative energy analyses

Following the conceptual matching of energy requirements of different types of minerals processing operations with energy products that could be generated from the sun, the methodology proceeded to illustrate this more quantitatively with a range of case studies, representing a range of the possible combinations in the matrix shown in Table 5. Energy analyses were conducted based on the flowsheets and information available for the selected case study operations. In the case where there was some level of uncertainty, literature values were used to validate the results.

In cases where there was not enough information available from literature, assumptions were made and in some cases information available for other similar operations was used. On the Etango Uranium refinery, information regarding energy consumption for each unit was not readily available instead the overall energy consumption of the whole plant was used as it was the only available information. The process flowsheet was therefore used to assess the type of end-use energy products required.

3.2.5 Sites selected for this study

In selecting sites for the first part of the work plan, an attempt was made to cover a representative range of minerals processing type operations as depicted on the matrix shown on Table 5. The selection criterion was based on the different ore grades being processed and typical flowsheets for such grades. Also included in this criterion was the typical mode of energy supply and the locations for such operations.

The following sites have been selected to form part of this study:

The operations selected are summarised as follows:

Etango Uranium mine represents the precious metals industry with trace amounts of the product mineral in the ore i.e. ppm grade. It is located in a grid remote area with diesel generators being utilised to supply the energy demands. The energy products required for this operation is AC electrical output and steam. This operation produces an oxide product and therefore does not incur the energy intensive step of reduction where the oxide is reduced to a metal.

Anglo Platinum's Rustenburg Base Metals Refiners is a base metal refining industry and they process ore with low grades, in the 0.1-1.0% range (Feng & Aldrich, 2000). It is located within the proximity of an electricity grid. Their power demand is met by the national power utility. The energy products required for this operation include AC & DC electrical output along with thermal power.

Skorpion Zinc Refinery represents the base metals industry that also processes low grade ore. It is located in a grid-remote area. Their power supply is sourced from the national grid via long distance grid extension. The required energy products for this operation include AC & DC electrical output and thermal power. However, as their thermal needs are met by an integrated chemicals and heat production scheme, the scope of this study for their operation covers only their electrical power demand.

Escondida Copper is a base metals operation with different grades and types of ore being processed. Their power demands are met by independent power producers (IPPs). It is located in a grid-remote area. The energy products required by their operations include AC, DC electrical output and steam.

(The main difference between the Skorpion Zinc operation and Escondida copper is that Escondida presents a variety of energy supply and demand scenarios. The Concentrators within Escondida have an AC load only and the Refineries (Oxide and Sulphide) have a combination of AC and DC loads.

The **Manganese Metal Company** processes high grade ore. The refinery is located close to the electricity grid and the national power utility supplies their power demands. The energy products required by this operation include AC & DC electrical output along with thermal power. For this study, only the electrical demands will be assessed. This is because the thermal energy demands require coal to be used both as an energy source and as a reductant in the Calciner.

The sites selected for this study thus do not comprehensively explore the matrix shown in **Figure 9**, presenting only a single exploratory case for the ferrous and trace categories, but exploring variation in location and in processing routes for the minor element category through three cases. The selection of cases, whilst informed by the matrix in Table 5 as well as considerations of access to and distance from the electric grid, were moderated by the availability of operating information and useful data that was required to execute this study. The only case not representative of a typical mineral processing operation in its class is the high grade ore case, which commonly refers to ferrous metals. The processing of ferrous metals generally does not involve electrolysis, and therefore there is no need for DC electrical power; Manganese processing as outlined in this study however involves electrolysis.

3.3 Methods

Meteorological data for the sites where each of these operations are located were used to size and analyse a utility scale solar PV power plant quantitatively and also inform a qualitative analysis of the use of concentrated solar power to meet the energy demands. A comparison between the designed solar energy plant with the conventional fuels currently used by these operations was done. As a basis for the comparison, each of the utility scale power plants were designed to produce an excess of 40 % of the load under design conditions⁷. This was done because the output of the solar array varies throughout year due to seasonal changes and throughout the day due to the position of the sun in the sky. There is no difference in the methodology employed; the same scenarios used to obtain the results presented in both Chapter 4 and 5. The only difference is that in Chapter 5, the results are also presented on an hourly basis).

3.3.1 Metrics to inform the 1st hypothesis test

The following metrics were used to establish how attractive the co-location of solar energy would be for each of the selected operations:

- (1) Synergies - refer to the combined effect of using renewable energy and co-locating the power supply to the consumer⁸. This study investigates the energy losses that can be avoided as a result of this synergy.
- (2) Losses (electrical) - the electrical losses covered in this analysis include transmission line losses and conversion losses. In a case where diesel generators are used for direct electricity generation and fuel tankers are used for transportation, these refer to the fuel consumption due to transportation.
- (3) Intervention by solar energy – presents three figures for each operation, viz. monthly load, needed backup and excess energy produced. In the case of Etango

⁷ Design conditions for a photovoltaic cell are a temperature of 25°C and solar radiation of 1000 W/m²

⁸ This refers to the minerals processing refinery

Uranium mine which is off-grid and utilises diesel generators for power supply, an extra figure which presents the state of charge of batteries is also included.

3.3.2 Detailed design of a solar power plant for a single operation: 2nd Hypothesis test

The results obtained from the comparison between the different operations were used to select an operation which has a potential of yielding significant gains from the use of solar energy. Solar PV technology was used as the technology of choice in this assessment, since PV is a more mature technology. The selection of a case for detailed analysis was done for a site with a significant DC demand.

3.3.2.1 Developing scenarios to test the hypothesis

For the detailed design of a solar power plant, 3 different scenarios were considered:

- Current/Base case: The conventional power plant currently used to meet the electricity demands of the minerals processing operation.
- Co-location: Co-locating a solar power PV plant with the selected minerals processing operation.
- Centralised: A solar power PV plant located away from a solar minerals processing operation on a site which has a good solar radiation.

These scenarios were used to compare the transmission line losses and conversion losses that would be incurred for each scenario. This comparison was to establish how co-location will affect these losses.

3.3.2.2 Transmission line and conversion losses

The results from the different scenarios were used to quantify the gains and losses for each scenario.

As outlined in 2.3.1 the $P_{\text{Loss}} = I^2R + I^2X$ has been used to evaluate the transmission line losses.

- Resistance and reactance are affected by temperature, considering that temperature fluctuates throughout the day, they were both evaluated at standard conditions.
- For this study the losses have been quantified at a standard temperature of 25°C.
- The length of the transmission line was established using google earth tools and information supplied by the utilities supplier in the countries where these operations are located.
- The length of the transmission voltage was taken into consideration to evaluate the transmission losses associated with each voltage strip. For instance, high voltage lines are expected less transmission line losses than low voltage lines.
- When power is converted from AC to DC and vice versa, 9 % of the power being converted is lost due to this conversion.
- This 9 % has been used to evaluate conversion losses in this study.

Conversion losses

The Conversion losses accounted for in this theses include AC – DC conversion, where power sourced from the grid is converted from the AC output to a DC output to meet the demands of the DC load where required. When solar power is in use, these losses refer to the DC - AC conversion to meet the AC load by the solar array and when excess power is generated from the array and has to be sent back to the transmission grid.

3.3.2.3 Synergies from co-location

The synergies are expected to come as a result of co-locating a solar power plant with a minerals processing operation. Co-locating a solar power plant with a minerals processing operation is expected to reduce the overall transmission line losses. During the daytime when the solar power plant generates enough power to meet the load of the minerals processing operation; these are expected to be a minimum.

The point of presenting the hour by hour analysis is to look at the energy supply of the solar resource on an hourly basis throughout the day. This is important because energy supply from the sun is not constant and needs to be monitored to assess how much back up from the grid would be required and how much excess power would be generated from the solar array.

3.3.3 Applicability of Meteonorm and Design Solar PV studio for simulating the performance of a solar power plant

Meteonorm V6 has been used to source meteorological data with the aid of Google earth to locate the co-ordinates of each of the selected sites. Meteonorm is a tool for comprehensive meteorological references, incorporating a catalogue of meteorological data and calculation procedures for solar applications and system design at any desired location in the world. It is based on over 25 years of experience in the development of meteorological databases for energy applications (Meteonorm 6.1, 2010).

Upon obtaining the meteorological data, it was used in Design Solar PV studio to design the solar power plants and simulate their performances. Design Solar PV studio is a suite of Windows 95, 98, NT, Win2000, and Vista compatible software designed to simulate photovoltaic energy system operation on an hourly basis for one year, based on a user selected climate and system design (Maui Solar Energy Software Corporation (MSESC), 2006).

Photovoltaic technologies have been explored and of all the available technologies presented, the c-Si modules which are the first generation of materials for solar modules as shown in section 2.2.1 have been used in the simulations because they are well established and have shown a good potential for utility scale application along with a good efficiency. For this study c-Si modules have been used as technology of choice when designing the utility scale PV solar power plant. Any of the other materials that have shown a good potential for utility scale application, efficiency and affordability can be used.

For the non-detailed solar power plants designed for all the operations a standardised capacity of 1.4 times the load was used for the sake of comparing the performance of the solar power plant at their locations and specific to the operation.

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Chapter 4 ASSESSMENT OF SELECTED MINERALS OPERATIONS FOR SOLAR POWER GENERATION

This Chapter presents operational information and an analysis of the constructed cases. Its purpose is to outline the energy demand and modes of supply, to lay the foundation for assessing how solar energy for electricity generation could affect the transmission line and AC-DC/DC-AC conversion losses that they experience. The analysis and results presented here are based on the process flowsheets and information that the operating companies have published or were willing to share. An analysis of how they could benefit from co-locating a solar power plant with their operations is also included. This forms an important part of this dissertation by presenting evidence in support of the first hypothesis outlined in Chapter 3.

4.1 Sustainability and renewable energy policies

This section discusses the operating company's policies regarding sustainability and renewable energy and their energy carbon footprint.

Etango Uranium is mainly owned by Bannerman Resources Australia. The company's commitment and responsibility regarding their carbon footprint and climate change is not mentioned directly in their sustainability and environmental policies.

Skorpion Zinc and **Anglo Platinum** operations are owned mainly by **Anglo American Limited Platinum Corporation**. They have strategies that underpin their approach to the global climate change and energy. These include a focus on energy efficiency through asset optimisation, carbon reducing projects, low-carbon technologies and adaptation to climate change. The Anglo American Limited Platinum Corporation group has committed itself to reducing their energy intensity by 15 % by 2014, based on the 2004 baseline. Over the decade to 2014, the group is aiming for a 10 % reduction in carbon dioxide emissions (Anglo American, 2010).

Escondida Copper is mainly owned by BHP Billiton. Mineral Escondida in particular is committed to the efficient use of energy, to the achievement of the highest standards in its processes and consequently to achieving the highest energy yield. And to motivate the organization in continuous improvement by promoting innovation and creativity focussed on reliability, costs and quality, in an environment of sustainable development and progressive reduction of greenhouse gas emissions (BHP Billiton, 2005). The company intends to promote the reduction of greenhouse gases associated with the purchase of energy.

The main shareholders at **MMC** are *Samancor* and *Delta SA*. There is no obvious policy towards sustainable energy supply for their operations.

Table 6 presents an overview of the case studies which include the current method of energy supply, expectation of how solar energy co-location with affect fuel usage, transmission and conversion losses along with the ore grade category being processed.

Table 6: Overview of case studies

Operation	Method of energy supply	Expectation: What could co-location with solar energy affect?	Ore grade category
Etango Uranium	Diesel generators	Fuel use	Trace
RBMR	Grid connected and Coal fired boilers	Conversion and Coal usage	Low
Skorpion Zinc	Grid extension	Conversion & Transmission	Low
Escondida Copper	Grid extension	Conversion & Transmission	Low
MMC	Grid connected	Conversion	High

4.1.1.1 Ferrous metals (More than 30 %)

To explore this case, MMC (Manganese⁹ Metal Company) has been selected. This operation processes high grade ore via a combined pyro- and hydro-metallurgical processing route and is located close to the electricity grid. Details on the operation of MMC are discussed in Chapter 3 of this study. High grade ore requires less energy input during the Comminution stage as less fine grinding is required for liberation.

4.1.1.2 Base metals (less than 5 % and more than 0.1 %)

Depending on which route is followed (energy intensive stages could require either thermal (in the form of steam or direct heat, where the source of energy is also a reagent in the reaction that occur in the thermal unit such as a Calciner), in such cases, the energy source cannot be replaced with solar energy without altering the process. Lower grade ore requires more energy input at the Comminution stage.

Escondida Copper operations which have a series of operations have been selected. These operations are in a remote desert-type location where electricity is sourced from independent power suppliers. These operations are located on a site which is said to experience one of the best solar radiations in the whole world. The refineries for these operations process low grade ore via the Hydrometallurgical processing route.

Skorpion Zinc has been selected. It is located on a remote desert-type site and the grid had to be extended for this operation to have access to power. This operation processes low grade ore via a Hydrometallurgical processing route.

RBMR was selected. It is located close to the electricity grid. The ore processed is residue from a precious metals ore. The whole process flowsheet from ore to final product includes both the Hydrometallurgical and Pyrometallurgical processing routes. This study only considers the base metals processing which follows the Hydrometallurgical processing route.

⁹ Manganese(Mn) is not exactly a ferrous metal but like iron ore which is ferrous, Mn ore has a high mineral content of more than 30 %

4.1.1.3 Precious metals (in ppm)

For these ores, high energy intensity is at the beneficiation (Comminution) stage. The lower the ore grade, the more energy input required to process it. Therefore, precious metals are expected to have a high energy input per ore processed.

Etango Uranium processes low grade ore via a combination of both Hydrometallurgical and Pyrometallurgical processing routes. It is located away from the electricity grid and land transportation infrastructure. Diesel generators will be used to supply power to this operation which is currently under construction to be commissioned in 2013.

These sites therefore make a good representation of the minerals processing industry because the different types of ore processed in this industry are covered. These include trace minerals content ore, low grade minerals content ore and high grade minerals content ore.

In terms of energy supply, the selected sites make a good representation of how most minerals processing operation have access to energy. These include, grid connected operations which are either located close or far from the grid, direct use of fossil fuels, and the use of generators for electricity supply.

The selection criteria were based on the different ore grades being processed and typical flowsheets for such grades. Also included in this criterion was the typical mode of energy supply and the locations for such operations.

4.2 Energy supply for the countries where these mines are located

This section presents the energy profile in the countries where these operations are located. Detailed energy supply information for each of these operations is included in Appendix B.

4.2.1 Resource availability for utility scale solar power plants

To assess the solar resource availability at the selected sites, they are compared with the sites that currently have the largest solar power plants in the whole world as depicted in Figure 10 below.

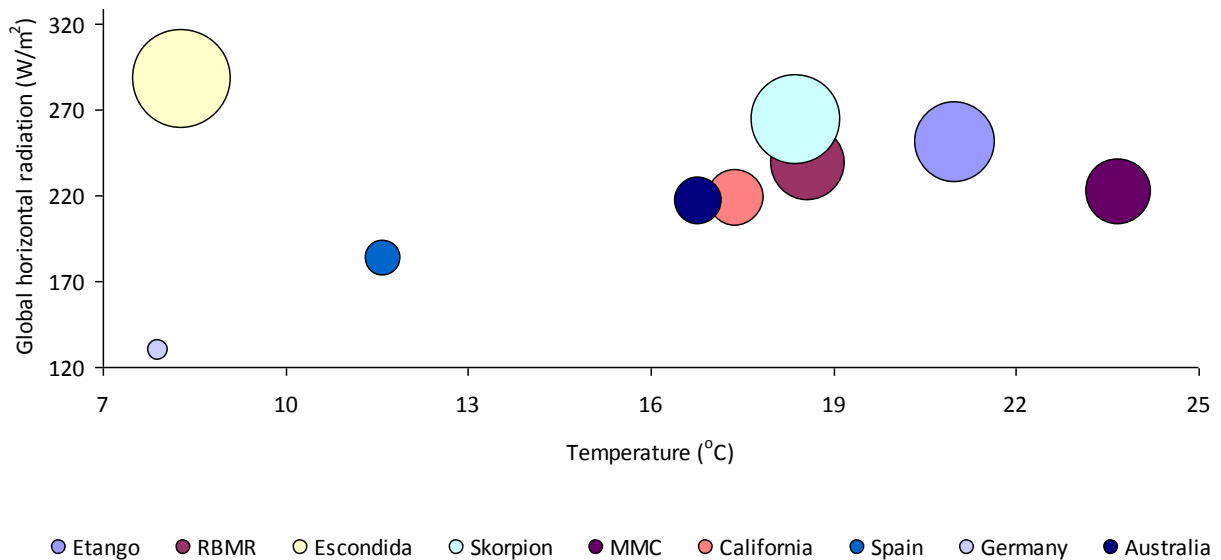


Figure 10: Comparison of the solar characteristics and energy demand of the selected sites with leading countries installations of utility scale solar power plants (year).

Germany and Spain have the lowest radiation yet in year they were the leading countries in the development of utility scale solar power plants. Australia, which is planning the largest solar power plant at 1 GW also has lower radiation levels. California which is currently benefiting from the use of REFIT programmes (Goswami, 2007) has radiation levels which are similar to Australia. From this information, it can be said that the selected sites have better radiation levels than the sites that currently have employed the use of utility scale solar power plants.

4.2.2 Namibian energy supply

The energy mix of Namibia is presented on the figure below with a total generating capacity of 380 MW. The country has a demand capacity of 428 MW and the deficit is sourced from neighbouring SADC countries, especially South Africa which has high fossil

fuel dependence. The energy mix shown is based on their generation capacity as presented on **Figure 11**.

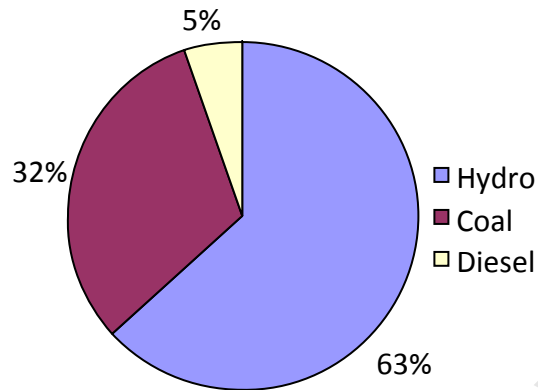


Figure 11: Namibia's energy mix based on their generation capacity (De Vita, Endresen & Hunt, 2006)

The Ministry of Mines and Energy (MME) is responsible for the national energy policy. Their mission is to regulate the responsible development, sustainable consumption and usage of the country's minerals and energy resources¹⁰. Nampower, a subsidiary of MME, is a state controlled power utility that holds a monopoly in electricity generation, import and transmission. Although government policies allow for the establishment of independent producers, no such companies exist to date at a utility scale¹¹.

The MME's white paper (Ministry of Mines and Energy, 1998) launched its First National Development Plan (NDP1) and one of the two main energy policy objectives of this plan is to drive the country towards a state of self-sufficiency in electricity generation by 2010. This is yet to be achieved since 11 % of the country's electricity supply is imported from South Africa. When operated at full capacity, the Skorpion Zinc refinery consumes 28 % of Namibia's power demands and is dependent on NamPower for supply. A 250 km

¹⁰ www.mme.gov.na

¹¹ www.nampower.co.na

long, 400 kV transmission line has been connected to the Nampower electricity grid to supply power to the Skorpion Zinc refinery (African Development Bank, 1999). This transmission line is connected to a longer 400 km transmission line from the Koeberg nuclear power station in South Africa.

4.2.3 South African Energy supply

South Africa, a partly industrialised country with an extensive mining and metallurgical industry, has been experiencing moderate economic growth in the past 20 years, and soon after its democratic transition ran a mass electrification programme. A lack of timely investment into new generation facility has recently seen demand for power outstripping supply (South Africa Energy Data, Statistics and Analysis, 2008). This has changed the status of energy supply. Although the cost of electricity has been previously ranked among the world's lowest, recent developments in the energy sector have driven an increase in the price of electricity by 24.5% for three consecutive years from 2010 and there was a big price hike of 30% in 2009 (Creamer, 2010b).

South African energy mix

The total generating capacity in South Africa is 36 208 MW (South Africa Energy Data, Statistics and Analysis, 2008). The electricity supply is mostly dependent on coal as shown on **Figure 12**, this is because the country has one of the most extensive coal reserves in the world (Generation Communication: Eskom, 2011). This is partly responsible for the low electricity tariffs compared to other parts of the world. With the decrease in coal reserves (Hartnady, 2010), and investment into new generation capacity to diversify the supply and replace ageing power plant, further electricity price hikes should be expected in the future.

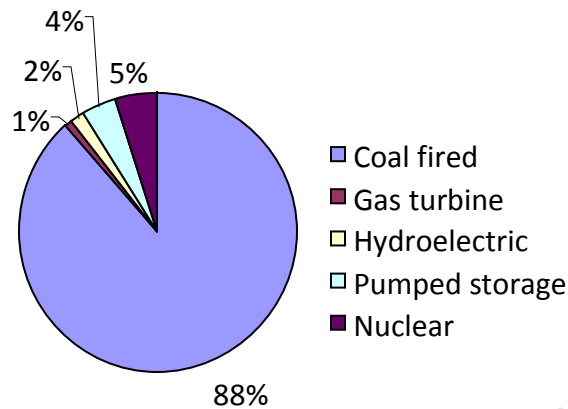


Figure 12: South Africa's energy mix based on the generating capacity (South Africa Energy Data, Statistics and Analysis, 2008)

4.2.4 Chilean Energy supply

Chile receives 70 % of Argentina's natural gas exports, which covers 37 % of the country's electricity demand (Speiser, 2008). Fossil-fuel-fired electrical plants were constructed to complement the building of hydroelectric dams in the 1990s (González 2004), when natural gas pipelines were extended across the Andes from Argentina to Chile's central and northern zones. The lack of investment for new exploitation of natural gas deposits led to the natural gas supply shortage in Argentina. This has reduced its exports in order to cover the increasing domestic demand that has resulted as a result of her economic recovery. Delivery of natural gas to Chile from Argentina has been cut by up to 14% (around 2.3 million cubic meters daily). Consequently, the arid Antofagasta and Atacama region in the Northern part of the country has been affected. This is further worsened by unavailability of hydroelectric energy sources. The use of diesel to alleviate the natural gas deficit has been suggested. Further, the government is currently promoting and increasing hydroelectric production and investigating the use of coal or oil for feeding the electrical plants in Northern Chile, although these routes are more expensive compared to the use of natural gas. This may impact the economic

situation of the country thereby resulting in increased electricity rates for consumers. The use of an alternative energy source such as solar may be preferable, as it could then be economical for Chile and the Chilean mines to invest in alternative sources of energy.

4.2.4.1 Chilean energy mix

The country has a total generation capacity of 9 700 MW. The Chilean energy mix is led by Hydro power followed by coal and then natural gas as shown on **Figure 13**. In the SING region, where the mines in this country are located, only fossil based fuels are used for electricity generation since there are no water reservoirs.

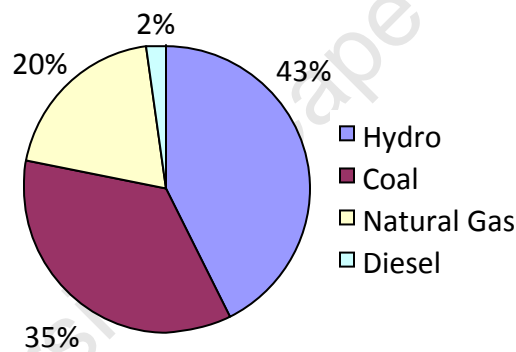


Figure 13: Chile's energy mix (Speiser, 2008)

4.2.4.2 Energy mix for Antofagasta area

Although located in Chile, the energy mix of the overall country does not represent that of the area where the Escondida Copper operations are located in Antofagasta which is dependent on fossil fuels for power generation. The operations are located at the heart of the Atacama Desert and connected to the SING grid for power access. The SING region has a total power generating capacity of 3 133 MW. The energy mix for the SING region where the Escondida Copper mine is located¹² is described on **Figure 14**.

¹² Atacama and Antofagasta area

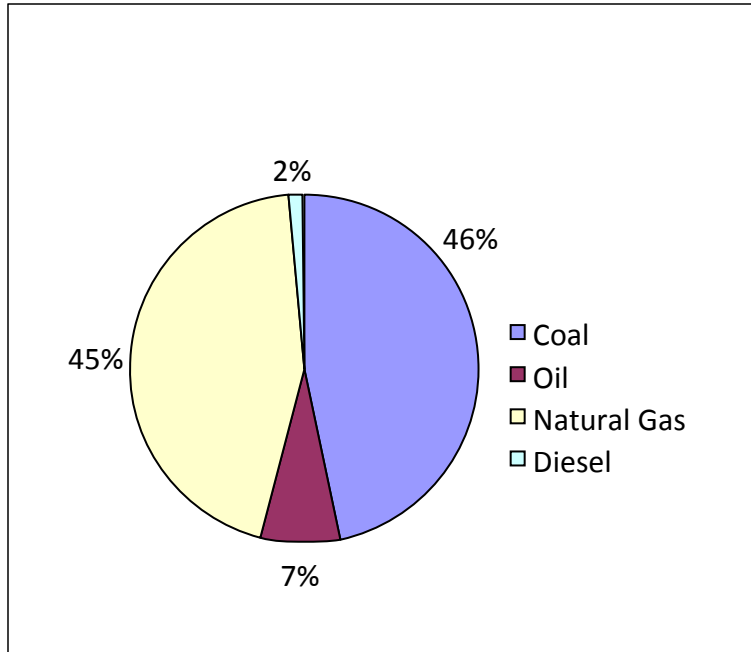


Figure 14: SING region's energy mix i.e. Atacama & Antofagasta (Speiser, 2008)

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4.3 Processing information and energy analysis for the selected operations

This section presents the process information which includes the process flowsheets and energy information along with the potential performance of a utility scale solar power plant for each of the selected operations. The detailed process information and data for the energy inventory covered in this section has been included in Appendix C. Appendix C also shows the methodology and sample calculations of how the electrical and fuel losses have been quantified.

4.3.1 Etango Uranium mine

The Etango Uranium mine is located in the Uranium rich Erongo area, on the western coast of Namibia and situated on the trend southwest of the Rossing Mine. The Rossing Mine is the longest-operated and second largest uranium mine in the world. The geology and potential bulk tonnage deposit of the Etango project is similar to the Rossing mine. In 2005, Bannerman Resources Limited, an emerging Uranium development company with interests in Namibia and Botswana was granted the titles for Uranium mineral licences in this area which has been identified as a prospective for Uranium mining and processing. The Etango operation would mine ore in a conventional open pit drill, blast and haul by truck and excavator/shovel operation, which is standard for hard rock mining operations. The mine has a life expectancy of 12 to 15 years (Bannerman, 2007).

4.3.1.1 Process flowsheet

The process flowsheet depicted on **Figure 15** shows the operation which handles 15 million tons of alaskite¹³ ore per annum to produce 2900 - 4000 tons of U₃O₈ per annum as a final product.

¹³ An oxide

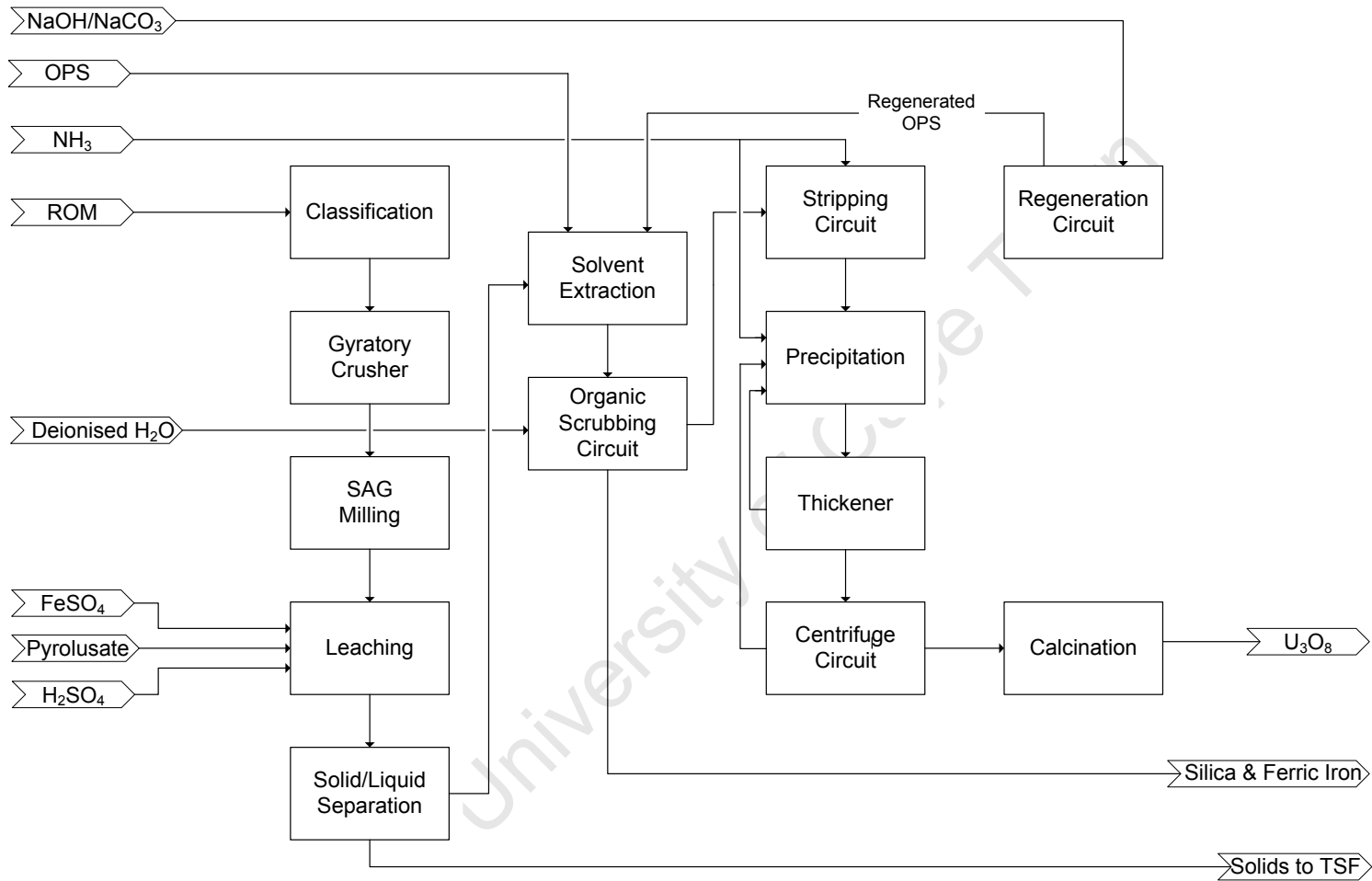


Figure 15: Process flowsheet for Etango Uranium refinery (Bannerman, 2007)

4.3.1.2 Energy consumption

According to the technical reports (Inwood, 2008) and media publications (Bannerman, 2007) concerning Etango Uranium mine, the process is expected to operate at a maximum power capacity of 30 MW. Although there are some media reports that have mentioned a capacity below this, the upper estimate will be used for this study. This value is given as an estimate single value since there was no available information to indicate how much energy each section on process flowsheet would consume. Table 7 shows the distribution of energy demands at Etango Uranium mine.

Table 7: Distribution of energy consumption at Etango Uranium

<i>Unit</i>	<i>Capacity (MW)</i>	<i>Energy</i>
Comminution	18	AC
Other	12	AC
Total	30	AC input

The power requirement of Etango Uranium mine has been estimated at 30 MW. Two options have been considered to supply this demand. The first one considers supply from the National grid. This will involve grid extension to the operation site. The company is currently in discussion with the government power utilities over this issue (NamPower, 2008). The second option involves the use of diesel generators to satisfy their AC electrical power output demand. In this case, diesel fuel will be used directly to fuel the plant's power demand. This option is not novel to the mining houses in this country, requiring Diesel transport on a regular basis to the operation site. This thesis explores this second option. Due to the limited power capacity of this country, some mines have to generate their own electricity to power their production demands. Shell supplies a nearby Uranium mine with Diesel to fire their generators. 21 000 litre diesel tanker trucks are used to transport the fuel from Walvis Bay to their operation which is 20 km away on a daily basis. The diesel tankers that Rossing Uranium is using to supply diesel to their operation is 21 000 litres. To date there has not been any published

record of how or if this operation is exploring the possibility of using renewable energy to supply its power demand.

The next sub-section presents the qualitative analysis for each of the selected studies as outline in section 3.2.4.

4.3.1.3 Utility scale solar energy potential at Etango Uranium

Table 8: Qualitative analysis of CSP vs. PV at Etango Uranium

Energy use/supply affected by:	PV	CSP
Reduced fuel transportation losses	Equivalent to day-time solar electricity augmentation	Beyond day-time if with thermal storage
Reduced fuel consumption	Significant during daytime	Significant during daytime and may extend beyond
Conversion losses	Significant, 100 % power input is AC	None
Co-produced heat	None	Significant augmentation of steam usage

It is fairly clear, that in this case, a CSP plant would be preferred on all four considerations shown in Table 8.

4.3.1.4 Estimation of synergies for a co-located PV plant

Whilst a CSP plant would be expected to show greater synergies, following the rationale and method described in section 3.2.4, the synergy of co-locating a PV plant at the Etango Uranium operation was estimated.

A diesel truck delivering fuel to this site would have to travel about 60 km inland to reach this ore processing plant. The fuel losses for transportation were based on this

assumption. A co-located solar power plant would reduce the number of trips that a diesel tanker would have to take during the daylight hours the ore processing plant would use solar power and diesel generators would only be required when the sun is not available. **Table 9** shows how co-location affect fuel usage from the base case.

Table 9: Annual diesel fuel used for base case and co-location at Etango Uranium

<i>Type of fuel consumption</i>	Base Case <i>Fuel loss</i> <i>(ML/annum)</i>	Co-location <i>Fuel loss</i> <i>(ML/annum)</i>	<i>Fuel consumption</i> <i>reduction from base</i> <i>case</i>
Fuel transportation	0.142	0.109	23%
Fuel to power inefficiency	17.7	13.6	23%
Power generation**	70.8	54.6	23%
Total diesel fuel used	88.7	68.3	23%

** This excludes the fuel losses due to the fuel-power inefficiency of the gen sets

4.3.2 Anglo Platinum’s Rustenburg Base Metals Refinery (RBMR)

Anglo American Limited Platinum Corporation is the world’s largest primary producer of Platinum group metals (PGM’s). The ore mined and processed by Anglo includes both the Merensky and UG2 reefs over the Bushveld igneous complex. These are sulphidic ores and contain both base and platinum group metals. Anglo Platinum’s processing operations include mines and concentrator plants which mill ore from the mining operations to produce PGM concentrate. This concentrate is treated at their 3 smelters (sited in Mortimer, Polokwane and Waterval) and two refineries i.e. Rustenburg Base Metals Refinery (RBMR) and Precious Metals Refinery (PMR) to produce saleable metal products as depicted in the figure below.

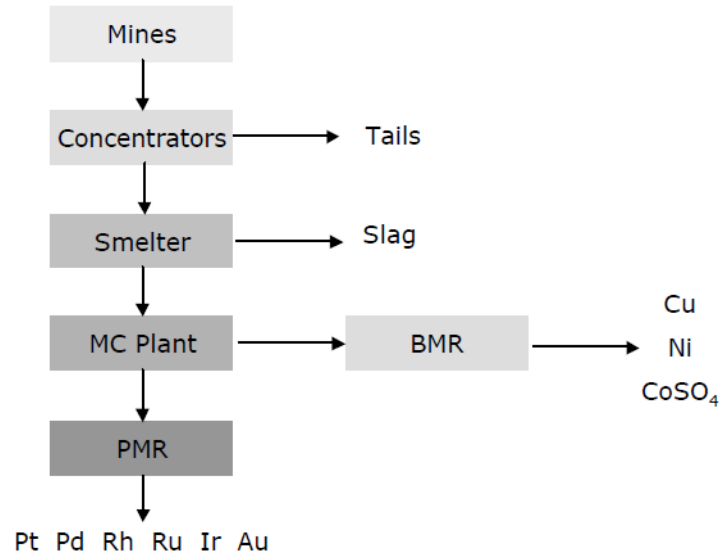


Figure 16: Anglo Platinum's operational process flowsheet (Anglo American, 2007)

The RBMR operation is divided into three subsections which consist of two metallurgical plants: The Magnetic Concentration plant (MC plant) and the Base Metals Refinery (BMR) as shown on **Figure 16** along with a steam generation plant. The scope of this study only covers the BMR and the steam generation plant due to availability of information on the operation and energy demands of these sections. This plant was visited to collate information relating to both these operations. The BMR processes converts feed from the MC plant to precious metals concentrate and base metals products. The precious metals are further refined at the PMR.

4.3.2.1 Process flowsheet

The BMR process is divided into three sections i.e. the **Leaching circuit**, **Nickel circuit** and the **Copper circuit** as shown on **Figure 17**.

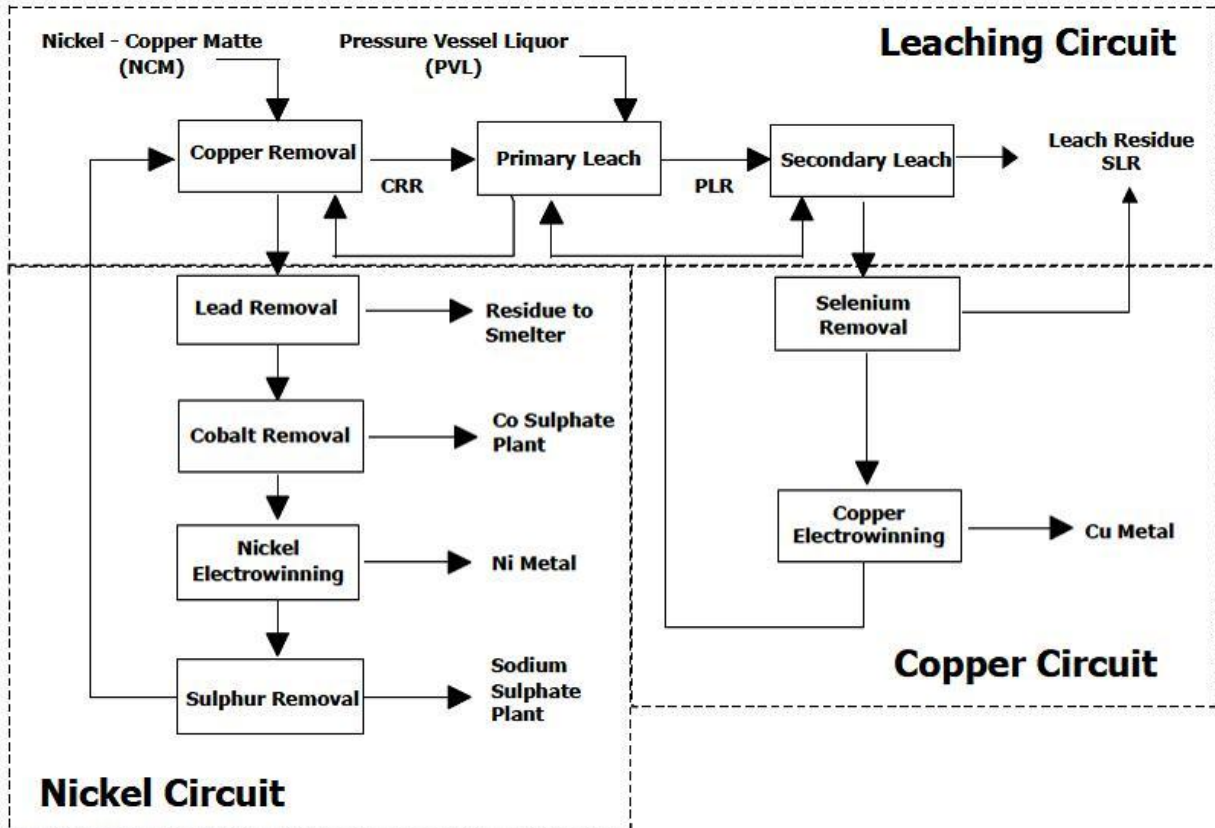


Figure 17: Anglo Platinum's Base Metals Refinery Flowsheet (Petersen, 2009)

4.3.2.2 Energy Demands

The electrical power capacity of the BMR is 17 MW with the distribution shown in Table 10. Currently the power is sourced from the South African power utility Eskom.

Table 10: Energy demands at Anglo Platinum's BMR

Operation	Capacity (MW)	Energy product
Electrowinning	14	DC electrical power
Copper circuits	3.2	
Nickel circuits	10.8	
Other	4	AC electrical power
Total	18	AC input

The Anglo Platinum base metals refinery is currently operating at a power capacity of 17.6 MW. This operation was undergoing an expansion programme which was placed on hold due to the global economic crisis which resulted in this company losing a recorded 96 % of its profits in 2009 (Seccombe, 2009). In this case study, the projected power demand as a result of the expansion will not be considered. The BMR is located in the North West province, where there are currently no power generating plants. The surrounding provinces have power stations which makes electricity accessible to this operation. When this plant was commissioned, electricity from the grid was easily accessible. From this point of view, the use of electricity supplied by the state power utility Eskom may be more economical than exploring renewable energy such as power from the sun. This operation is located close to the electricity grid and has easy access to electricity via the interconnected South African grid system. The nearest power stations with a base load capacity to supply this operation are in the Free State, Limpopo and Mpumalanga provinces of South Africa.

4.3.2.3 Utility scale solar energy potential

Table 11: Qualitative analysis of CSP vs. PV at RBMR

Energy use/supply affected by:	PV	CSP
Reduced transmission losses	During day-time, with some losses of over-produced power at peak	Beyond day-time if with thermal storage
Reduced conversion losses	Significant as 14/18 MW is DC	Insignificant
Co-produced heat	None	Significant augmentation of steam usage
Other synergies or penalties		Potential insurance against load-shedding or expensive power during peak demand

Table 11 shows that the overall analysis is inconclusive as both solar power options have some advantages – would need a quantitative comparison of avoided conversion losses (PV) vs. additionally avoidable transmission losses and co-produced heat (CSP). Such a comparison is beyond the scope of this dissertation.

4.3.2.4 Estimation of synergies for a co-located PV plant

Following the method described in section 3.2.4, the synergy of co-locating a PV plant at the RBMR was estimated.

The transmission line losses were based on the assumption that power requirement of this operation will be sourced from the closest power station that has enough capacity to power it. Considering that the S.A grid is inter-connected, the losses estimated on Table 12 could be an under-estimate compared to the actual losses.

Table 12: Annual electrical losses for base case and co-location of a PV plant at RBMR

<i>Type of electrical loss</i>	<i>Base Case Losses (GWh)</i>	<i>Co-location Losses (GWh)</i>	<i>Energy loss reduction from base case</i>
Transmission line	1.57	1.04	34%
AC-DC or DC-AC conversion	10.2	8.2	20%
Total losses	11.8	9.24	22%

The AC-DC losses are applicable for the Base Case scenario where the AC power sourced from the grid has to be converted to DC via rectifiers to meet the DC load. DC-AC losses are applicable to co-location.

4.3.3 Skorpion Zinc

Skorpion Zinc is the 8th largest Zinc mine in the world, producing Special High Grade (SHG) Zinc. It was owned and operated by Anglo American Limited Platinum Corporation as part of the Anglo Base Metals division, but has recently been sold. It is located in the South West of Namibia and is comprised of an open pit mine, mill, a hydrometallurgical alongside an electrometallurgical refinery and a casting house. It was first explored between 1976 and 1982 by Erongo Mining and Exploration, an Anglo American Limited Platinum Corporation subsidiary. The non-sulphide mineralisation ore body posed metallurgical processing difficulties in terms of refining (Skorpion Zinc, 2010). Although there are other zinc oxides deposits present around the world, these are currently uneconomic to explore (Balarini and others, 2008). According to (Skorpion Zinc, 2010), this is the only zinc processing facility to use solvent extraction-electrowinning metallurgy to process and refine zinc products, while other refineries with sulphide mineralisation use the conventional smelting and roasting processing routes. This is the first commercial application of Zinc SX-EW for processing primary leach liquor. The overall operation is summarised on **Figure 18**.

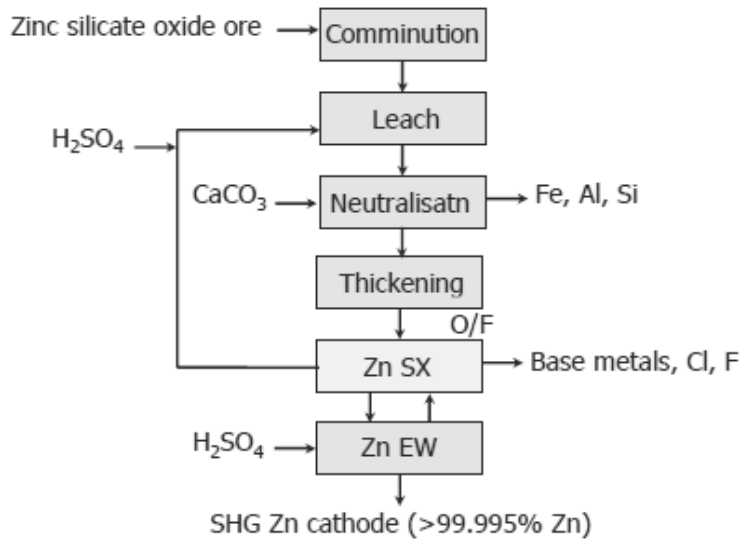


Figure 18: The flowsheet for Skorpion Zinc's operations (Skorpion Zinc, 2010)

4.3.3.1 Process flowsheet

Figure 19 shows the detailed process flowsheet for processing 1.5 million tons per annum of non-sulphidic ore to produce 150 000 tons per annum of 99.999 % Zinc metal at Skorpion Zinc.

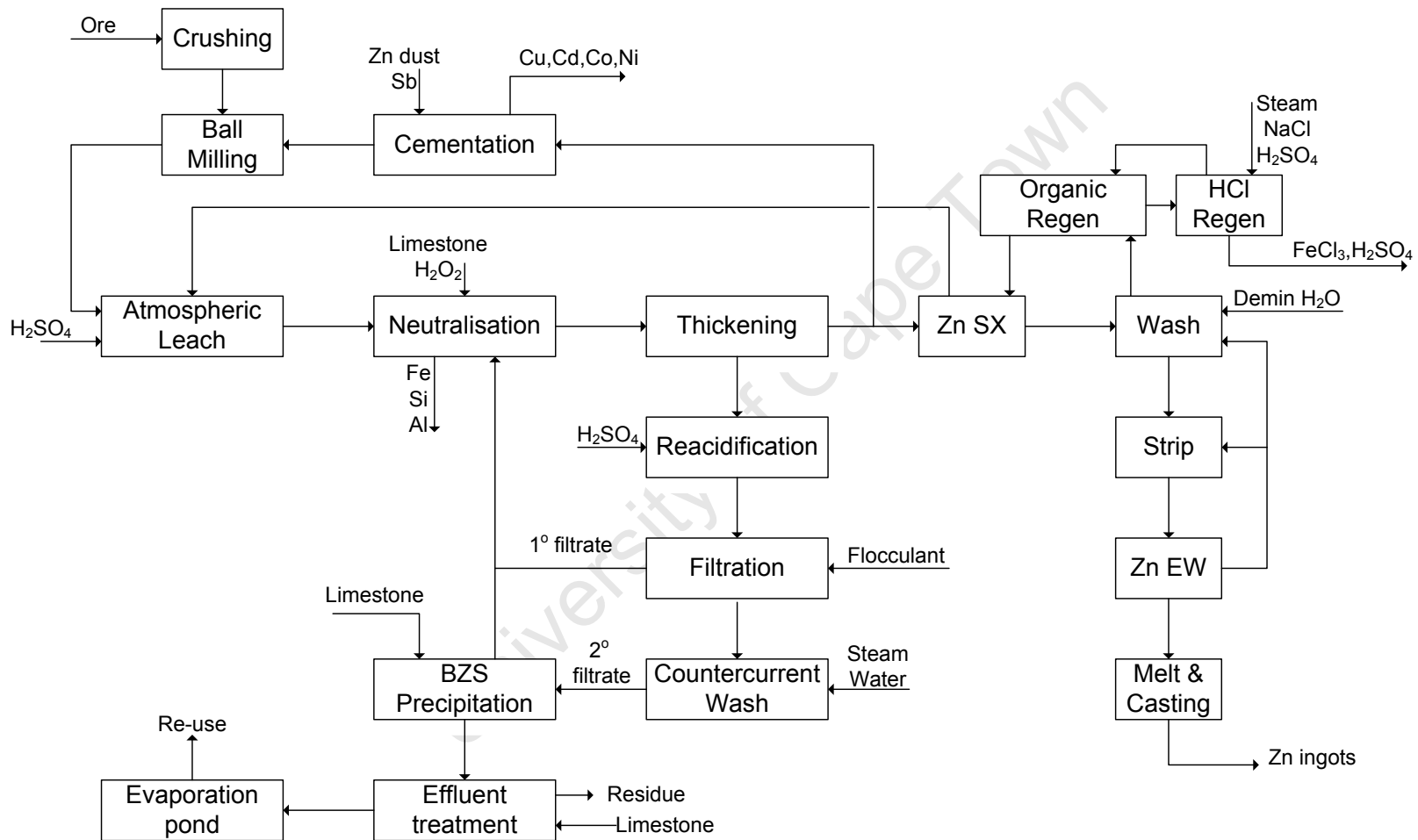


Figure 19: Detailed process flowsheet for Skorpion Zinc refinery (Bhikha, 2009)

4.3.3.2 Energy demands

The operation has an installed power capacity of 120 MW. This operation has increased Namibia's power demand by 25 %. When operating at full capacity, it is expected to consume 28 % of the country's power consumption. It has been operating at 106 % capacity since 2005 thus demanding 30 % of the country's power demand.

Table 13: Energy demand distribution for Skorpion Zinc's operation

<i>Unit</i>	<i>Capacity (MW)</i>	<i>Energy product</i>
Comminution to SX	30	AC
Steam generation	14	Thermal
Electrowinning	90	DC
Total	120	AC input

At the time when Skorpion Zinc was commissioned and inaugurated in 2003, the power requirement was estimated at 120 MW when the plant operates at full capacity as shown on **Table 13**. Since the plant was commissioned, it has at times operated above capacity with a recorded output of 150 400 tonnes in 2009 (Njini, 2010). This has placed an unexpected strain on the power supply. Only one option was considered to power this operation. The Namibian power grid was extended to Rosh Pinah where this plant is located. To date, there has not been any study or project which involves the use of renewable energy to supply the power demands of this operation. Although in during the grid extension and plant design, as part of their sustainability initiative and complying with the country's policies precautions were taken to protect the delicate Namib desert where the plant is located.

4.3.3.3 Utility scale solar energy potential at Skorpion Zinc

Table 14: Qualitative analysis of CSP vs. PV at Skorpion Zinc

Energy supply/use affected by:	PV	CSP
Reduced transmission losses	During day-time, with some losses of over-produced power at peak	Beyond day-time if with thermal storage
Reduced conversion losses	Significant as 90/120 MW is DC	Insignificant
Co-produced heat	None	Significant steam usage
Other synergies or penalties		Potential insurance against load-shedding or expensive power during peak demand

Based on Table 14 the overall analysis shows that both CSP and PV have advantages but due to the unavailability of water in this operation CSP could be impossible. Also, due to the high DC load, PV appears to present an opportunity of sizeably reducing AC-DC conversion losses. Therefore PV is the most preferred in this case.

4.3.3.4 Estimation of synergies for a co-located PV plant at Skorpion Zinc

Following the method described in section 3.2.4, the synergy of co-locating a PV plant at the Skorpion Zinc was estimated.

For co-location, the DC-AC conversion losses refer to the electrical losses incurred when the power generated from the power plant is converted to meet the AC load of the operation and the excess power produced is sent back to the grid. The AC-DC losses are applicable for the Base Case where rectifiers are used to convert AC power from the grid

to DC so that it meets the DC load. **Table 15** shows the energy loss reduction from base case.

Table 15: Annual electrical losses from base case and co-location at Skorpion Zinc

<i>Type of electrical loss</i>	<i>Base Case Losses (GWh)</i>	<i>Co-location Losses (GWh)</i>	<i>Energy loss reduction from base case</i>
Transmission line	159	103	36%
AC-DC or DC-AC conversion	71	61	14%
Total losses	230	164	29%

Co-location results in a significant reduction of transmission line losses because this operation involves a long distance grid connection and has a relatively high DC load. Therefore the overall electrical loss reduction of 29 % shows that co-location would be beneficial for this operation.

4.3.4 MMC (Manganese Metal Company)

Manganese Metal Company (MMC) is the single largest producer of pure electrolytic manganese metal in the world. MMC produces only selenium-free electrolytic manganese (the purest form of manganese) to meet the world demand. The refinery (production facility) is located in Nelspruit, in the Mpumalanga province of South Africa. The metal is produced from the South African high-grade manganese ore, extracted via a hydrometallurgical process. A range of products is manufactured from the metal and packaged according to individual demand. The use of a selenium-free process technology ensures 99.9 % minimum metallic purity and it facilitates human health and environmental safety. MMC has been producing pure electrolytic manganese since 1960. The production capacity is 27 000 tonnes per annum, from a single cell house (Electrowinning circuit).

4.3.4.1 Process flowsheet

The process flowsheet described in Figure 20 which shows the simplified which processes 75 000 tons per annum ore which is mined in the Kalahari Desert to produce high purity¹⁴ 28 000 tons per annum Manganese metal (MMC, 2007).

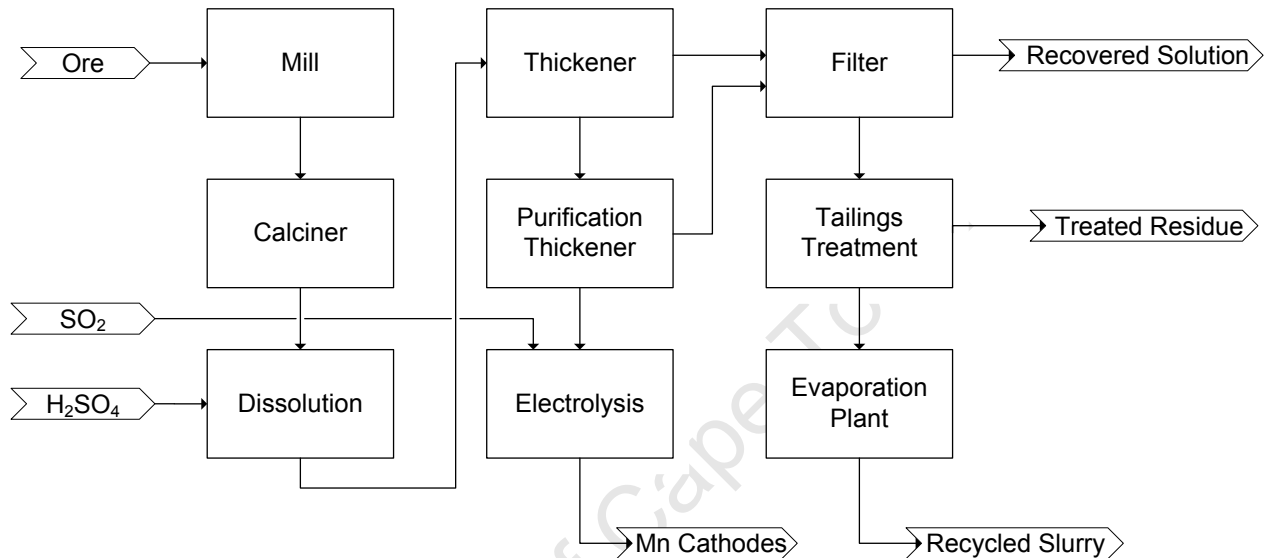


Figure 20: Simplified process flowsheet for Manganese Metal Company (MMC, 2007)

4.3.4.2 Energy demand and supply

The section labelled as: Other plant units; includes the following units: Mill, Calciner, Dissolution, Thickener, Purification thickener and Filter. The Tailings treatment and evaporation plant are not included since they fall outside the boundaries of the refinery itself.

Table 16: Energy demand distribution for MMC's refinery

Unit	Capacity (MW)	Energy product
Other plant units	15.0	AC
Electrolysis	6.7	DC
Total	21.7	AC input

¹⁴ 99.9 % purity

This refinery is located relatively close to the electricity grid. It operates at a total capacity of 21 MW as shown on Table 16. In the area where this plant is located, there is not enough open space suitable for land-mounting of PV modules.

4.3.4.3 Utility scale solar energy potential at MMC

Table 17: Qualitative analysis of CSP vs. PV at MMC

Energy supply/use affected by:	PV	CSP
Reduced transmission losses	During day-time, with some losses of over-produced power at peak	Beyond day-time if with thermal storage
Reduced conversion losses	Insignificant	Insignificant
Co-produced heat	None	Insignificant steam usage
Other synergies or penalties		Potential insurance against load-shedding or expensive power during peak demand

Based on Table 17, the overall analysis shows that this operation is located relatively close to the transmission grid; therefore transmission line losses are not significant in each case. The conversion losses are not significant either as only 6.7/21.7 MW requires DC electrical input. Based on this, the synergies are weak in both cases.

4.3.4.4 Estimation of synergies for a co-located PV plant at MMC

Following the method described in section 3.2.4, the synergy of co-locating a PV plant at the RMBR was estimated.

The AC load for this operation is high; therefore the power generated for the solar power plant has to be converted from DC-AC before the AC load is met. As a result, the

AC-DC electrical losses are expected to be high when a solar power plant is co-located with this operation. The energy loss reduction from base case is presented on **Table 18**.

Table 18: Annual electrical losses from base case and co-location at MMC

<i>Type of electrical loss</i>	Base Case <i>Losses (GWh)</i>	Co-location <i>Losses (GWh)</i>	<i>Energy loss reduction from base case</i>
Transmission line	1.59	1.08	32%
AC-DC or DC-AC conversion	5.28	7.37	-40%
Total losses	6.88	8.46	-23%

The negative impact that co-location has is mainly attributed to the conversion losses as shown on the table above. This operation is an example of an operation where solar PV technology is not suitable. This is mainly due to the high DC-AC conversion losses that the operation has to incur when a PV solar power plant is co-located with this operation.

4.3.5 Escondida Copper Mine

Escondida is the world's largest copper producer using the open pit mining process. It is also one of the lowest cost copper producers (BHP Billiton, 2009). It is located in Chile's Atacama Desert, 170 kilometres from Antofagasta (BHP Billiton, 2009). The Escondida mine produces copper concentrate by means of the sulphide ore floatation process and also produces copper cathodes using the oxide ore leaching and low-grade bio-leaching processes. The company produces around 360 million tonnes of minerals annually. The infrastructure consists of: Two open-pit mines (Escondida and Escondida Norte, which is located 5 kilometres from Escondida); two concentrator plants (Laguna Seca and Los Colorados); an electrowinning plant to produce cathodes from oxide and sulphide ore and two pipelines that transport copper concentrate from the mine to the filter plant, which is located at the Port of Coloso, in the far south area of the city of Antofagasta. The facilities include a seawater desalination plant meant to supply water for the processes. These operations are summarised in **Figure 21**.

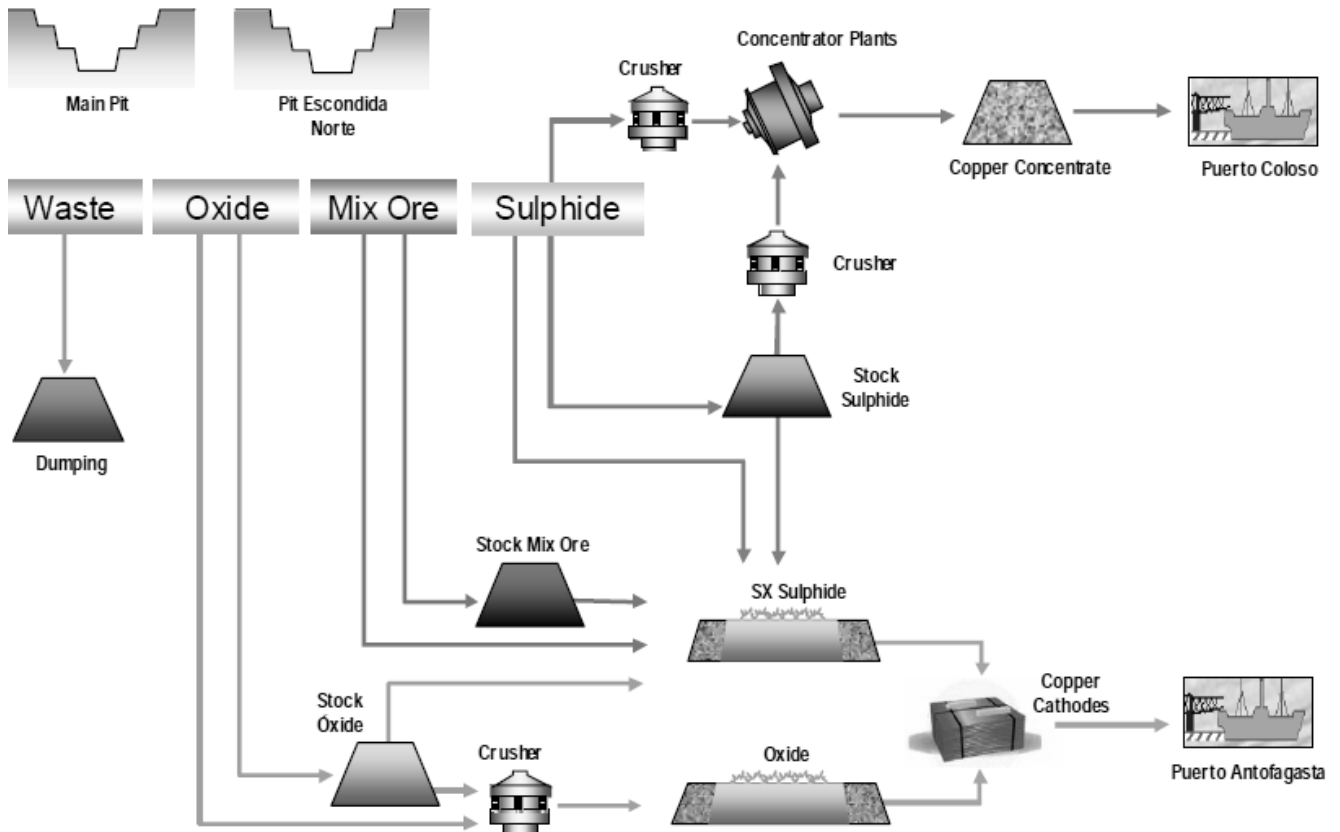


Figure 21: General process flow diagram of Escondida operation (Minera Escondida, 2007)

Escondida copper has four different operations for processing the ore that is mined from their open pit mines. These include: Two concentrators Laguna Seca and Los Colorado with power demand of 134 MW and 147 MW respectively and two processing plants sulphide ore processing plant and oxide ore processing plant at capacities of 88 MW and 84 MW respectively. Although these operations are not far apart i.e. they are within a radius of 10 km of each other, they are not located on the same site, for these reason they will be treated as separate cases. This operation and the other related operations which service it directly currently have a load profile which constantly requires over 500 MW capacity of electrical power. Their operations are very energy intensive and require power supply continuously 24 hours a day and 365 days a year. Therefore a disturbance in the stable supply of electricity can easily cost the operation millions of dollars in a single day. In 2007 BHP Billiton as a company reported CO₂

emissions of 52 million tonnes and these were primarily from energy consumption which is fossil based (BHP Billiton, 2005).

One of the challenges that BHP Billiton is currently facing is obtaining efficient, secure and low cost sources of energy. Escondida operations are located in a remote area, has a tremendous scale and a predictable flat power demand power profile (Bandyopadhyay and others, 2008). As part of their sustainability policies, the company is committed to operate in more environmentally friendly technology and renewable energy is included in this. The high cost of interruption and the nature of high dependency on electricity for this operation show that a more reliable and cleaner electricity source is required.

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4.3.5.1 Concentrators

The concentrator plants treat sulphide ore at capacity of 230 000 tonnes per day. Los Colorados and Laguna Seca has a processing capacity of 120 000 tpd and 110 000 tpd respectively. The copper concentrate produced by both plants is conveyed through two slurry pipe lines to the Coloso Port facilities located south of the city of Antofagasta. At Coloso the pulp undergoes a pressure filtering process producing a concentrate of 9 % humidity. The concentrate is later shipped by land or ocean freight to consumers around the world. The simplified process flowsheet for the concentrators at Escondida is shown on Figure 22.

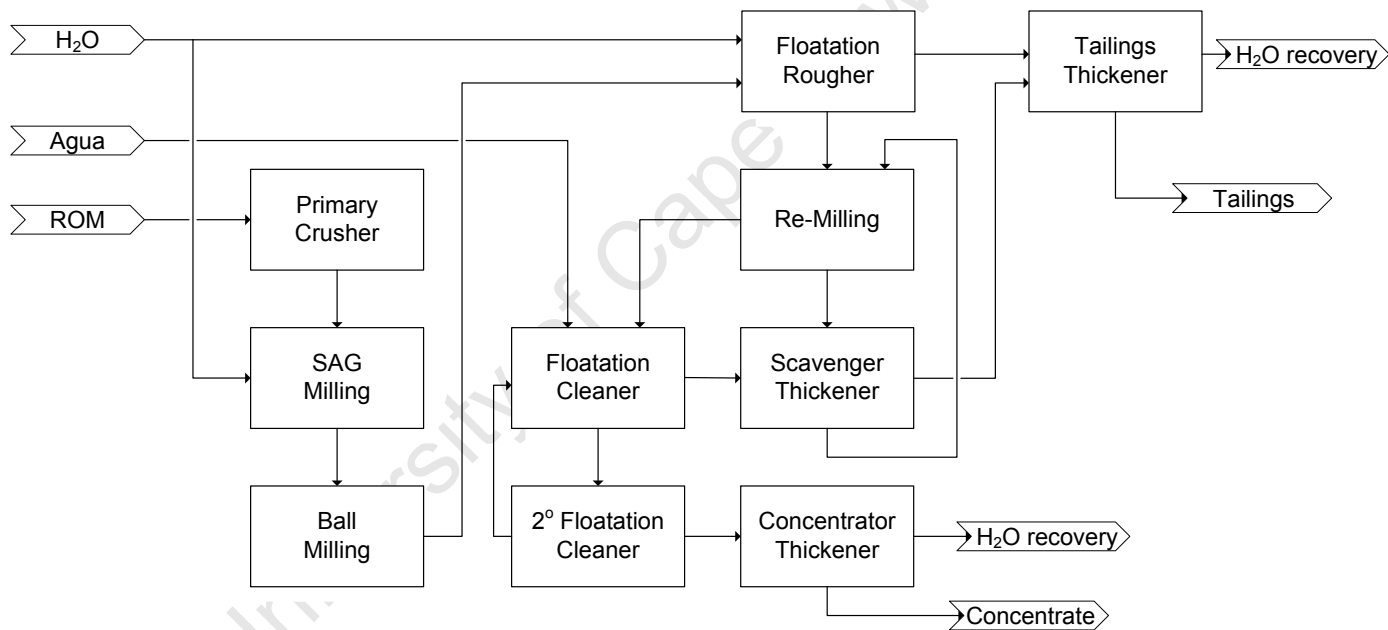


Figure 22: Schematic diagram of the concentrators at Escondida Copper (BHP Billiton, 2004)

4.3.5.2 Energy consumption for the concentrators

Table 19: Averaged electrical capacity per annum at the concentrators

Unit	Capacity (MW)		Energy product
	Laguna Seca	Los Colorados	
Primary crusher	9	10	AC
SAG mill	54	59	AC
Ball Mill	51	56	AC
Flotation circuit	20	22	AC
Total	134	147	AC input

Table 19 shows that the overall energy input required for the concentrators in AC electrical and there is no DC load.

4.3.5.3 Utility scale solar energy potential at the Concentrators

Table 20: Qualitative analysis of CSP vs. PV, at the concentrators

Energy use/supply affected by:	PV	CSP
Reduced transmission losses	During day-time, with some losses of over-produced power at peak	Beyond day-time if with thermal storage
Reduced conversion losses	Introduces new conversion losses	None
Co-produced heat	None	None

Based on Table 20, the overall analysis shows that both cases reduce transmission line losses but PV introduces DC-AC conversion losses that do not currently exist. Therefore CSP would be the preferred solar technology but the unavailability of water could deter the other technologies, leaving the Dish Stirling as the technology of choice within CSP.

4.3.5.4 Estimation of synergies for a co-located PV plant at the concentrators

Following the method described in section 3.2.4, the synergy of co-locating PV plant for Laguna Seca and Los Colorados respectively was estimated.

The Los Colorados and Laguna Seca operation do not have a DC load. Therefore all the power generated from a PV solar power plant has to be converted from DC to AC resulting in AC-DC conversion losses.

Table 21: Annual electrical losses for base case and co-location at Los Colorados

<i>Type of electrical loss</i>	Base Case <i>Losses (GWh)</i>	Co-location <i>Losses (GWh)</i>	<i>Energy loss reduction from base case</i>
Transmission line	180	110	39%
AC-DC or DC-AC conversion	0	41	
Total losses	180	151	16%

Table 22: Annual electrical losses for base case and co-location at Laguna Seca

<i>Type of electrical loss</i>	Base Case <i>Losses (GWh)</i>	Co-location <i>Losses (GWh)</i>	<i>Energy loss reduction from base case</i>
Transmission line	157	96.4	39%
AC-DC or DC-AC conversion	0	37.4	
Total losses	157	134	15%

Based on the results presented on

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Table 21 and Table 22, it is clear that if there were no DC-AC conversion losses, co-location would result in 39 % reduction in energy losses instead of the 16 %. This implies that a solar PV technology is not the best technology for these operations although the co-location results in a reduction in energy loss.

4.3.6 Sulphide ore

The sulphide ore processed is of marginal copper grade and is leached through a bacteria assisted oxidation process to produce 213 000 tons of copper cathodes per annum. The simplified process flowsheet is presented on Figure 23.

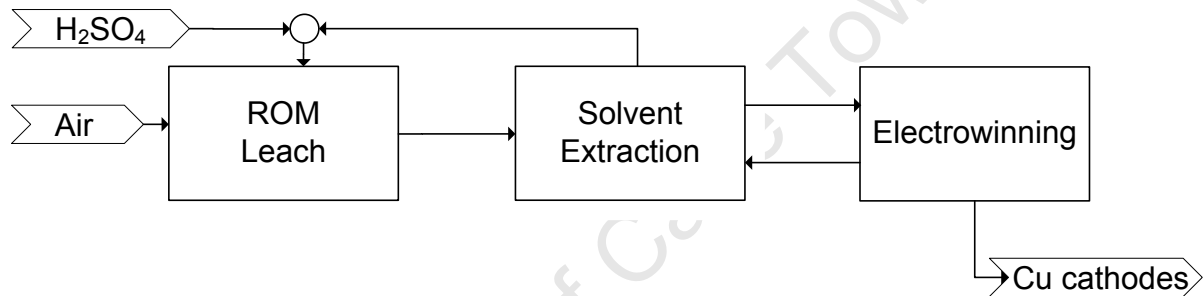


Figure 23: Simplified process flowsheet for Sulphide ore refinery (Outotec, 2009)

4.3.6.1.1 Energy demands for the sulphide ore flowsheet

The energy demands for the sulphide ore process flowsheet are shown on **Table 23** along with the specific demand for each process unit.

Table 23: Averaged electrical capacity per annum for the sulphide ore flowsheet

<i>Unit</i>	<i>Capacity (MW)</i>	<i>Energy</i>
ROM leach	10	AC
Solvent extraction	30	AC
Electrowinning	58	DC
Total	98	AC input

Utility scale solar energy potential for the sulphide ore

Table 24: Qualitative analysis of CSP vs. PV, for the sulphide ore

Energy use/supply affected by:	PV	CSP
Reduced transmission losses	During day-time, with some losses of over-produced power at peak	Beyond day-time if with thermal storage
Reduced conversion losses	Significant as 58/98 MW is DC	Insignificant
Co-produced heat	None	Significant steam usage
Other synergies or penalties		Potential insurance against load-shedding or expensive power during peak demand

Based on Table 24, the overall analysis is inconclusive as both solar power options have some advantages – would need a quantitative comparison of avoided conversion losses (PV) vs. additionally avoidable transmission losses and co-produced heat (CSP). Such a comparison is beyond the scope of this dissertation.

4.3.6.2 Estimation of synergies for a co-located PV plant for the sulphide ore

Following the method described in section 3.2.4, the synergy of co-locating PV plant at the sulphide ore was estimated. The energy loss reduction from base case is presented on Table 25.

Table 25: Annual electrical losses for base case and co-location for the sulphide ore process flowsheet

Type of electrical loss	Base Case Losses (GWh)	Co-location Losses (GWh)	Energy loss reduction from base case
Transmission line	37	22.7	39%
AC-DC or DC-AC conversion	45.7	39.9	13%
Total losses	82.7	62.6	24%

4.3.6.3 Oxide ore

Escondida began processing oxide ore at the end of 1998. The oxide ore which is mainly extracted from the Escondida pit is sent to the oxide plant (BHP Billiton, 2009). This ore is processed to produce 150 000 tons of copper cathodes per annum. The simplified process flowsheet is presented on Figure 24.

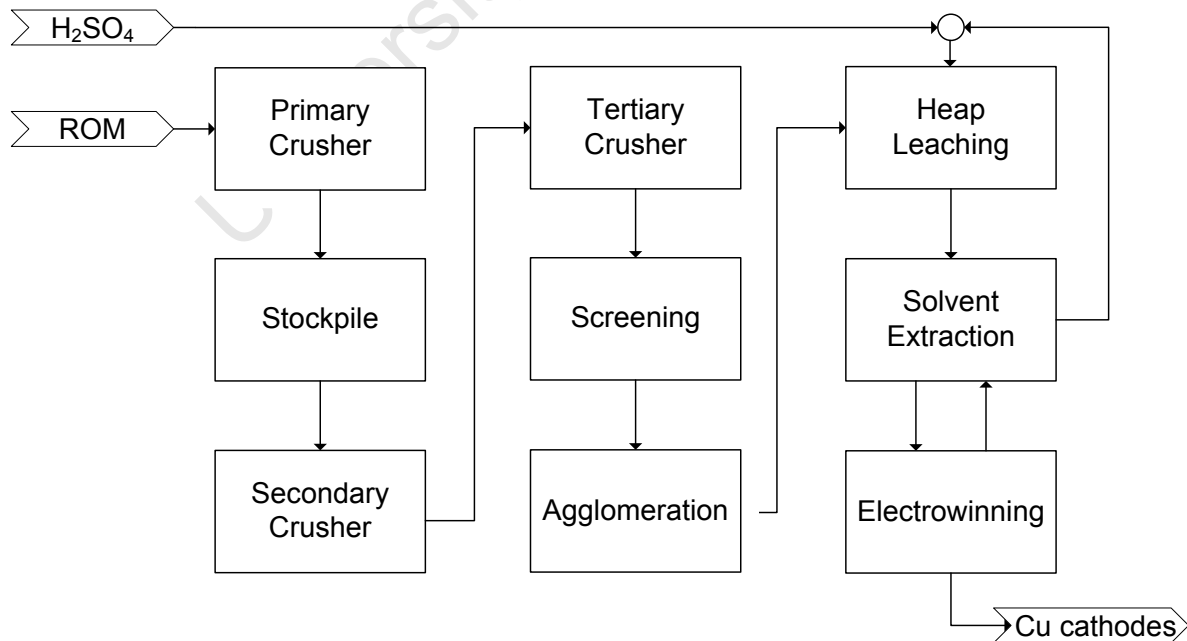


Figure 24: Process flowsheet for Oxide ore refining (BHP Billiton, 2004)

4.3.6.3.1 Energy demands

Table 26: Averaged electrical capacity per annum for oxide ore flowsheet

<i>Unit</i>	<i>Capacity (MW)</i>	<i>Energy product type</i>
Primary crusher	7.0	AC
Secondary crusher	3.0	AC
Tertiary crusher	3.0	AC
Heap leaching	7.0	AC
Solvent Extraction	21	AC
Electrowinning	41	DC
Total	82	AC input

Table 26 shows that the energy input required for the oxide ore flowsheet is 50 % DC and 50 % AC.

Utility scale solar energy potential for oxide ore

Table 27: Qualitative analysis of CSP vs. PV, for the oxide ore

Energy use/supply affected by:	PV	CSP
Reduced transmission losses	During day-time, with some losses of over-produced power at peak	Beyond day-time if with thermal storage
Reduced conversion losses	Significant as 41/82 MW is DC	Insignificant
Co-produced heat	None	Significant steam usage

Based on Table 27, the overall analysis is inconclusive as both solar power options have some advantages – would need a quantitative comparison of avoided conversion losses (PV) vs. additionally avoidable transmission losses and co-produced heat (CSP). Such a comparison is beyond the scope of this dissertation.

4.3.6.4 Estimation of synergies for a co-located PV plant for oxide ore

Following the method described in section 3.2.4, the synergy of co-locating a PV plant at the oxide ore was estimated.

The AC-DC conversion losses are applicable for the base case. DC-AC conversion losses are only incurred when the PV solar power plant has to meet the AC load.

Table 28: Annual electrical losses for base case and co-location for oxide ore flowsheet.

<i>Type of electrical loss</i>	Base Case <i>Losses (GWh)</i>	Co-location <i>Losses (GWh)</i>	<i>Reduction from base case</i>
Transmission line	27.0	16.6	39%
AC-DC/DC-AC conversion	32.3	33.7	-4%
Total losses	59.3	50.3	15%

Based on the results presented on **Table 28**, it can be deduced that for this particular operation and site, when the DC load is equal to the AC load, co-location results in an increase in conversion losses. This increase in conversion losses could be a result of the excess power generated from the designed solar power plant. This introduces a further question for this study i.e. at what capacity should a PV solar power plant designed to minimise conversion losses? This question will be addressed in the next Chapter which will also address the 2nd Hypothesis formulated for this study in Chapter 3.

4.4 Discussion

The previous sections in this Chapter have considered how co-location would affect the transmission and conversion losses in each of the selected cases. This section presents a comparative analysis.

Table 29: Summary of transmission line energy losses

Operation	Base Case	Co-location	Transmission distance¹⁵ (km)	Reduction from Base Case
RBMR	1.57	1.04	600 EHV + 50 HV	34%
Skorpion Zinc	159	103	80 HV	35%
MMC	1.59	1.08	100 EHV + 80 HV	32%
Los Colorados	180	110	200 EHV + 75 HV	39%
Laguna Seca	157	96.4	200 EHV + 69 HV	39%
Sulphide Ore	37	22.7	200 EHV + 74 HV	39%
Oxide ore	27	16.6	200 EHV + 65 HV	39%

The results presented on Table 29 above, suggest that co-location of a solar power plant with the selected sites results in at least 32 % reduction in transmission line energy losses annually.

This shows that when a solar power plant is co-located with each of these operations the transmission line losses that these operations are currently would be reduced by the respective percentages presented on the table above. Furthermore, solar thermal technologies have the potential of reducing these transmission losses and conversion losses for operations that have an AC load only. The next table has summarised the conversion losses that these operations are currently experiencing when a utility scale solar PV power plant is co-located with each of the operations. The summary from this table will be used to elaborate on the technology of choice for each of these operations and the possible gains that can result from solar thermal technologies.

¹⁵ Lines used for electricity transmission include both EHV (Extra High Voltage) and HV (High Voltage)

Table 30: Summary of conversion losses

<i>Operation</i>	<i>Base Case</i>	<i>Co-location</i>	<i>Percentage DC</i>	<i>Reduction from Base Case</i>
RBMR	10.2	8.2	78%	20%
Skorpion Zinc	71	61	75%	14%
MMC	5.28	7.37	31%	-40%
Los Colorados	0	41	0%	-
Laguna Seca	0	37.4	0%	-
Sulphide Ore	45.7	39.9	59%	13%
Oxide ore	32.3	33.7	50%	-4%

Table 30 above shows that there are cases where the use of solar PV is attractive and others where it is not. Based on this table, operations which have a DC load of more than 50 % seem to benefit from the use of solar PV technology. Operations such as MMC and the Oxide ore flowsheet which have a DC load of 50 % and less seem to experience an increase in the conversion losses. In the case of Laguna Seca and Los Colorados which do not have a DC load, the use of solar PV introduces conversion losses that were not there in the base case. For these operations, solar thermal technologies would be favourable as the solar array will produce AC electrical power as required by the load directly. There will be no need for rectifiers and DC-AC conversion losses will be avoided altogether.

Skorpion Zinc shows the highest reduction in losses at 29 % from the base case, with the transmission line losses reduced by 36 %. These transmission line losses account for almost 70 % of the overall losses at this operation. The conversion losses are reduced by 14 %. The transmission line losses are reduced by at least 32 % from the base case by co-location in all the cases studied. Co-locating thus clearly would have a positive impact on reducing the transmission line losses. However, in the case of conversion losses, the reduction on conversion losses is dependent on the type of load that the solar power plant has to meet along with the capacity of that load.

This implies that in a case where there is both a DC and AC load, the conversion losses can either increase or decrease depending on the capacities of each of the loads. For a DC load that is small compared to the AC load, the conversion losses become significant as seen with the MMC study where co-locating results in an increase in the overall losses instead of the desired decrease. This could be attributed to the fact that this operation is located relatively close to the electricity grid and has a large AC load which exaggerates the DC-AC conversion losses. Therefore the transmission line losses do not account for much compared to the conversion losses.

In the case of Los Colorados and Laguna Seca where the load is only AC, a solar power PV plant introduces DC-AC conversion losses which are not there in the base case. However, these losses are offset by the avoided transmission line losses resulting in the overall losses being reduced by 16 and 15 % respectively when a solar power plant is co-located with these operations. A CSP plant producing AC power would further reduce losses associated with conversion, and additionally could offer an advantage of running for longer than just daylight hours, extending the avoided line losses too.

The Anglo BMR shows a similar load distribution as the Skorpion Zinc Refinery but the difference is that BMR is located closer to the grid and has a smaller electrical capacity than SKZ, therefore has less transmission line losses; SKZ also has a better solar resource than BMR. These are the main reasons why the reduction in losses from the base case for BMR is lower than those seen for the SKZ study.

The Sulphide and Oxide flowsheets for Escondida Copper exhibit a good example of how the capacity of either DC or AC affects the conversion losses. The oxide has an equal DC and AC load and the overall conversion losses increase by 4 % instead of decreasing, whereas for the Sulphide flowsheet where the DC is higher than the AC load, the overall conversion losses are reduced by 13 %.

4.5 Comparison for all the sites/operations as a basis for selecting a site with a good potential for the use of solar energy

This section compares the annual solar fraction and excess power generated from the designed solar arrays obtained for each of the operations on a percentage basis to establish which of these operations would benefit the most from the use of solar energy. The criteria compared include: Average annual solar fraction, Average percentage of loss incurred by each of the operations and percentage of excess electricity generated by the solar power plants on site. These results are presented in detail for each operation in Appendix E.

When a PV solar power plant is designed, it is important to note that the output power from the array will vary throughout the day and this is dependent on the time of the day and the position of the sun. As outlined in Chapter 3, the PV solar power plant for each operation has been designed to meet 1.4 times of the load under standard conditions. As a result, excess power which could be saleable will be produced by each of the designed solar arrays.

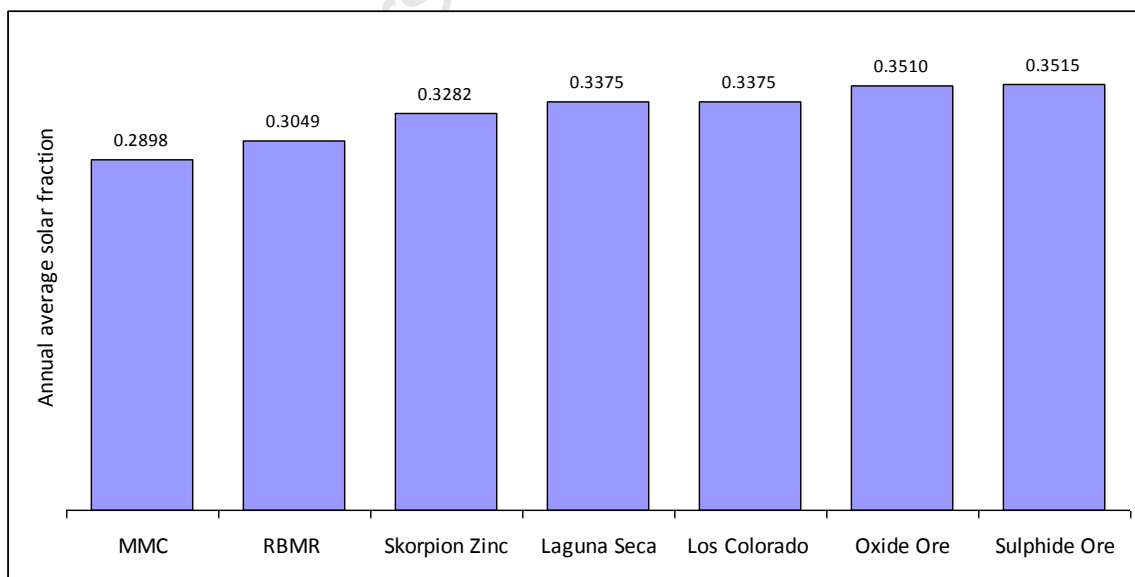


Figure 25: Comparison of the annual average solar fraction for the different operations

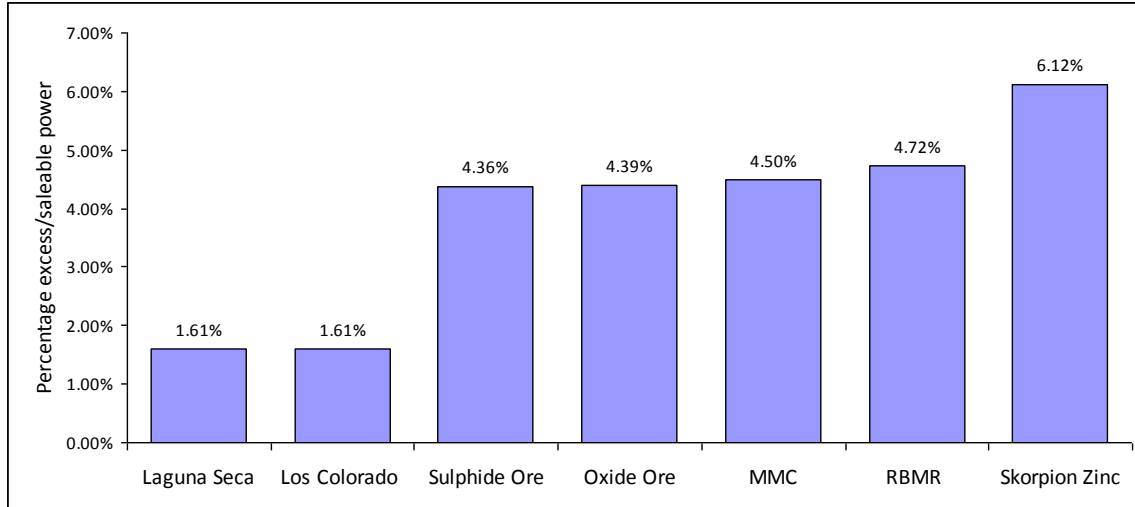


Figure 26: Comparison of excess electricity generated from the solar power plants

Figure 26 shown above, the excess power generated for each of the designed solar power plants. Skorpion Zinc when designed to meet the same fraction of the load as all the other operations shows the potential of producing 6.12 % excess power above its load capacity. The excess power that could be produced by each of the plants on a month to month basis is presented in the appendix.

The difference in solar fraction for the AC and DC supply indicate that using solar energy for DC supply shows a better solar fraction compared to AC supply. Figure 25 shows that Laguna Seca and Los Colorados which only have an AC load; have a lower solar fraction compared to the other operations which have a DC load. This finding accounts for the conversion losses that result from converting of DC (product of PV solar power) to AC by inverters and the fact that inverters continue to consume electricity even when they are not being used to convert electricity. From this observation, it can be concluded that operations with a high DC load would benefit from the use of solar energy harnessed through PV installations.

4.6 Concluding remarks

Based on what has been presented in this Chapter, it can be concluded that the studied locations, with the possible exception of MMC, have a rich solar resource which has not yet been harnessed to meet their energy demands. This Chapter presented detailed information about the operation of these mining sites and their energy demands, along with their potential to accommodate utility scale solar power plants based on the available solar resource at their site.

The qualitative analysis has shown that operations with a pure AC load (exemplified by Etango Uranium, and the Escondida concentrator plants) would benefit from the use of solar thermal technologies as these technologies produce AC power directly without the need of rectifiers. This would avoid DC-AC conversion losses involved when solar PV technologies are used to meet an AC load.

The following have been used as selection criteria for an operation which should be investigated further by conducting a detailed study on how a solar power plant would have an effect on the energy supply.

- Operation experiencing high losses
- Operation showing a high solar fraction

From the results presented in this Chapter, the Skorpion Zinc Refinery emerges as a suitable operation for a more detailed solar power plant design. This is because of all the operations connected to the electricity grid; it is the one which is currently experiencing the highest electrical losses due to transmission and conversion, estimated at an annualised power loss of 26 MW. The site where it is located has the 2nd best solar radiation after the Escondida operations.

Chapter 5 ENERGY SUPPLY FOR A REMOTE OPERATION: EXISTING SYNERGIES BETWEEN A CO-LOCATED SOLAR POWER PLANT WITH THE SKORPION ZINC REFINERY

This Chapter analyses in more detail how a solar power plant co-located with the Skorpion Zinc Refinery could perform. The main objective of this Chapter is to explore some of the technical details related to a utility scale solar power plant installed at a remote minerals processing operation, and also to evaluate the reduction or increase in energy losses from the base case scenario as a result of either co-locating a solar power plant with the refinery or having a solar power plant in the next best location¹⁶ closest to the refinery.

5.1 Technical design of a co-located PV solar power plant

Power to the refinery is supplied via a long distance transmission grid. This operation requires both an AC and DC electrical input, therefore, a solar array with two components has been designed to meet the electrical demands of the 90 MW DC load and the 30 MW AC load. The solar power plant system would be connected to the electrical grid which would be used to meet the load demand that the solar array cannot supply and receive the excess power that the array would be producing during peak hours. The DC power plant would supply the electrowinning circuits at the Tankhouse directly and the AC the rest of the plant with the use of inverters. The single biggest power consumer on the plant is the electrowinning cellhouse, in which a bulk¹⁷ of the power is used via the electrowinning rectifiers which are fed at 66kV with an output

¹⁶ Based on solar radiation data compared to the solar resource where the Skorpion Zinc refinery is located.

¹⁷ about 80 %

current of 55 kA. The rest of the plant is fed by two 55 MVA 66/11 kV transformers via a network of substations at 11 kV, 3.3 kV and 525 V (Bateman Engineering, 2000).

5.1.1 Orientation and set-up of the solar array

The orientation for a PV solar power plant depends on the desired power output from the plant, as this dictates the components required. The voltage and current output have been designed to meet the demand from the load by including an MPPT (see section 2.2.1.1 controller in the design. This means that for the electrowinning circuit, which is sensitive to both voltage and current changes, the MPPT controller balances the power supply such that fluctuations do not affect the performance of the refinery and production. The use of a solar power plant should not change the operation of the refinery. The current power supply set up is shown in **Figure 27** for the AC load and DC loads.

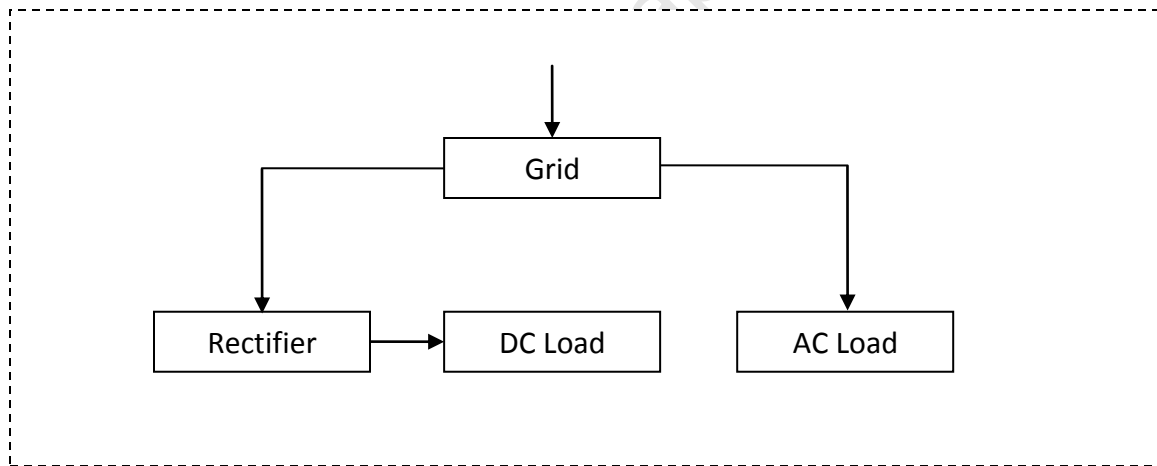


Figure 27: Schematic of the current set-up used for power supply

5.1.2 The AC solar power generation plant for the 30 MW AC load

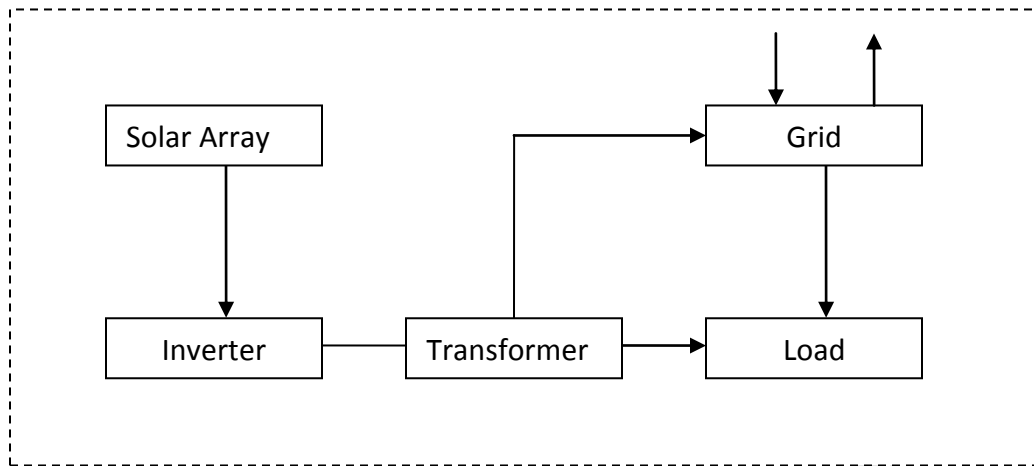


Figure 28: Schematic of the simplified design of the solar power plant to meet the 30 MW AC load

Figure 28 demonstrates the solar array which converts light from the sun to produce DC electrical power. The output from the solar array is sent through an inverter where it is converted to an AC electrical output. The solar array generates low voltage power and to match this with power required by the load, a transformer is used to step up the voltage, so it matches both the grid and the load at any time. The power produced by the array is sent through to match the load, when this is not enough, the grid supplies the deficit and when the array produces excess power, it is sent to the grid and sold to the utility power supplier.

5.1.3 The DC solar power generation plant for the 90 MW DC load

For the DC power plant, a set-up which is similar to the AC power plant is used. The difference between these is that for the DC power plant, an inverter is used to convert the excess power generated by the array from DC to AC so that it is compatible with the power from the grid before it is sent back to the electricity grid.

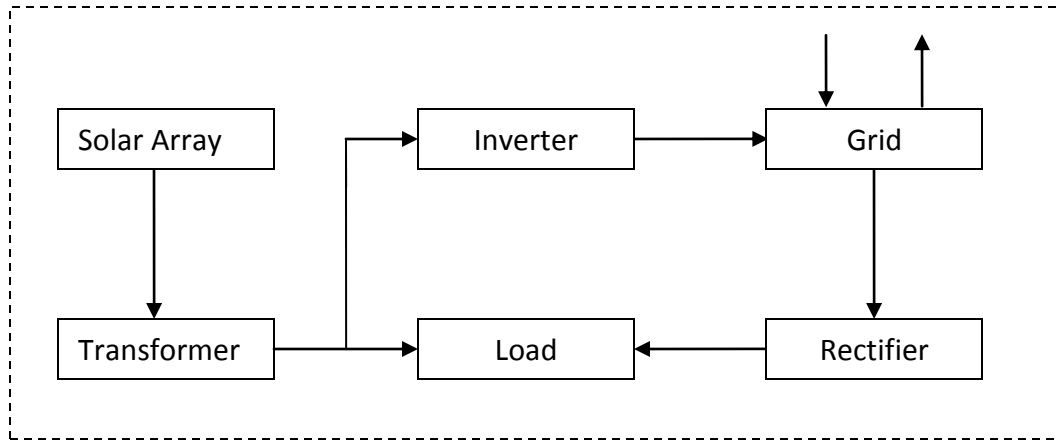


Figure 29: Schematic of the simplified design of the solar power plant to meet the 90 MW DC load

Figure 29 demonstrates the schematic of the solar array which converts light from the sun to produce DC electrical power. A transformer is used to match the power from the array with that required by the load and excess power from the array is sent through an inverter where it is converted to AC output to match the waveforms of the grid line. When the power generated by the array is not enough, the grid supplies the deficit and when excess power is generated, it is also sent back to the grid.

5.1.4 Technical information and land availability

A solar PV power plant does not particularly require a flat terrain for the modules, although a non-flat terrain does pose technical issues when assembling the array onto the ground. The area where the Skorpion Zinc Refinery is located has a flat topography and there is enough land¹⁸ required to accommodate both an AC and DC power plant of the capacities stated in **Table 31**. Therefore land availability does not pose a limitation on the required capacity of the solar power plant. The co-ordinates system used to determine the direction of the array are shown on **Figure 30**.

¹⁸ Google earth was used to verify this visually

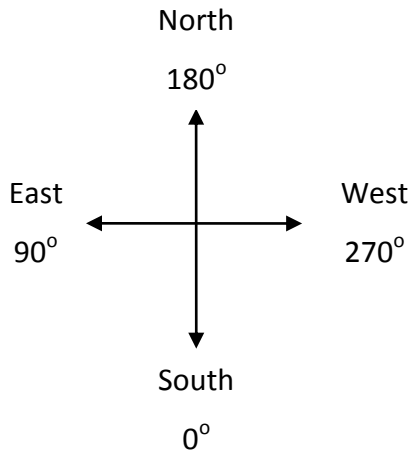


Figure 30: Co-ordinates system used

Table 31: Technical parameters for the solar power plants

<i>Type of plant</i>	<i>AC electrical output</i>	<i>DC electrical output</i>	<i>Combined electrical output</i>
Plant capacity ¹⁹	37.5 MW	112.5 MW	150 MW
Load capacity	30 MW	90 MW	120 MW
Annual array output	8 MW	41 MW	49 MW
Tracking method	Fixed slope and azimuth		
Array slope ²⁰	20°		
Array azimuth	180°		
Distance between modules	1.2 m		
Number of modules in array	126 000	374 000	500 000
Solar panel power rating	300 W		
Array area (hectares)	76	224	300

¹⁹ Max power rating at standard conditions

²⁰ Elevation/tilt from the ground

The solar modules on the array are mounted on a fixed slope and azimuth instead of tracking the direction of the sun. As stated in Chapter 2, using trackers would add an extra cost while increasing the annual solar fraction by a relatively small fraction.

5.2 Results

The results presented in this section include: The **optimal size** for the solar power plants, development and analyses of **different scenarios** that were considered to supply electricity to the Skorpion Zinc Refinery and compare each to the base case which is the current mode of energy supply, and the resulting **electrical losses** from each scenario based on the optimal size along with the average **hourly output** on an annual basis.

5.2.1 Optimal size

Sizing a solar power plant depends on how much of the load has to be supplied by the solar power plant at different times of the day with minimal losses. Figure 31 shows total annual losses as a factor of the over-design factor at peak insolation. As discussed in section 2.3, there are two types of losses: i) the transmission line losses which are dependent on the power and distance over which this power is transmitted and ii) the AC-DC/DC-AC conversion losses which are dependent on the size of the solar power plant.

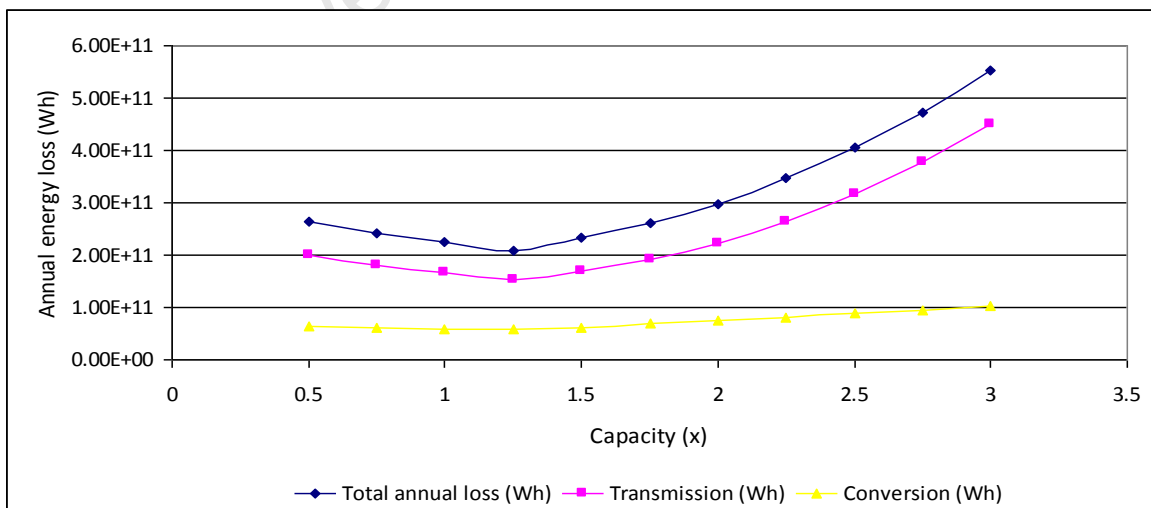


Figure 31: Estimated annual electrical losses for the overall solar power plant versus the capacity to supply a 120 MW load

The optimal capacity of the solar array is presented on **Figure 31**, is further assessed by looking at the optimal array size required to meet the DC and AC load on **Figure 32** and **Figure 33** respectively.

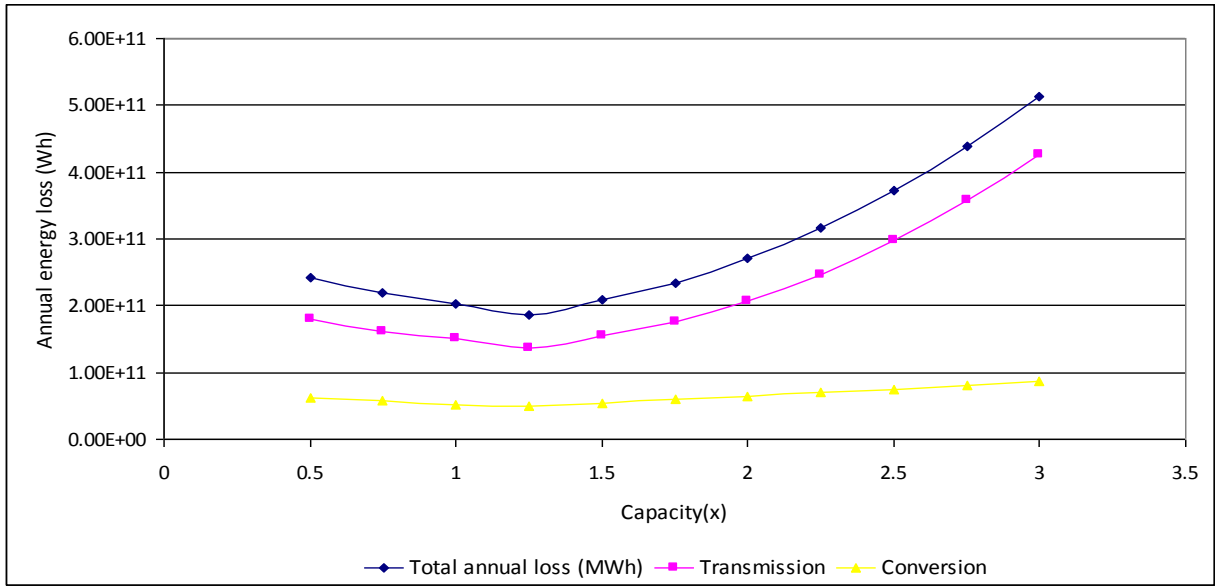


Figure 32: Estimated annual losses versus the capacity of a solar power plant to supply a 90 MW DC load

When the solar array designed to meet the DC load at this operation, the capacity controls the transmission line losses than the conversion losses. When the capacity is increased, the DC-AC conversion losses are increased; these conversion losses reach a minimum when the capacity is 1.25. When the solar array is designed at a capacity of less than 1.25, the conversion losses increase. When excess power is produced, the DC-AC conversion losses are increased and transmission line losses are increased as this power has to be transmitted over the electricity grid. When the array is designed at a capacity of less than 1.25, the AC-DC conversion losses increase as the AC power from the grid has to be rectified to DC electrical power.

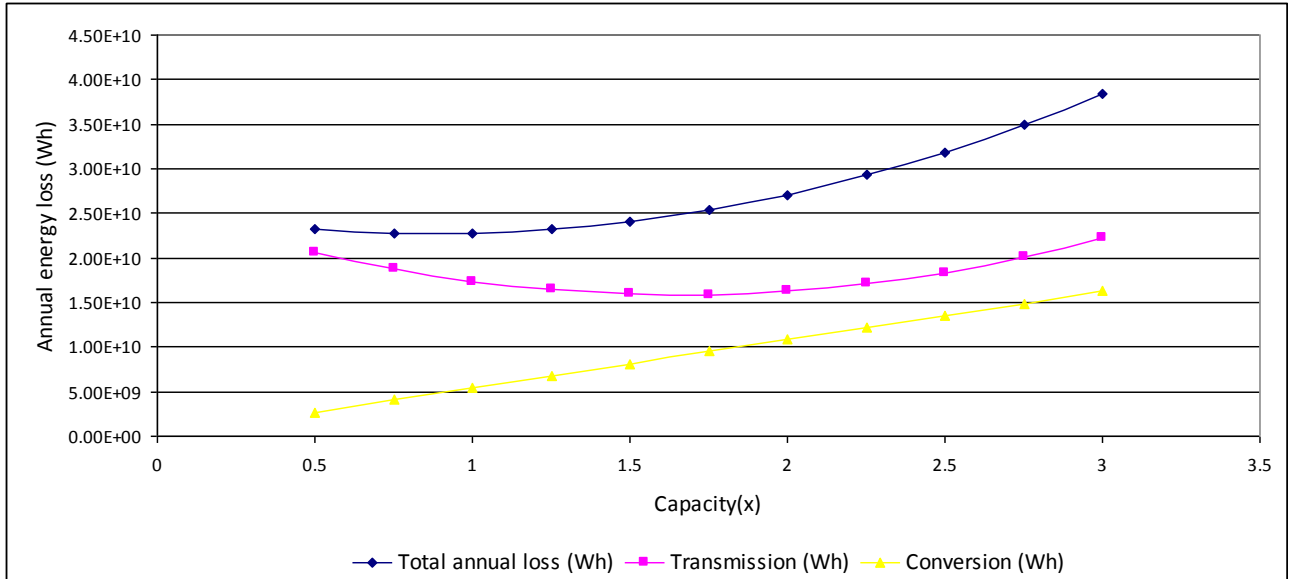


Figure 33: Estimated annual losses versus the capacity of a solar power plant to supply a 30 MW AC load

When the array is designed to meet the AC load, DC-AC conversion losses are introduced when a PV solar power plant is used to meet an AC load. The figure above supports this because when the capacity of the array is increased, the DC-AC conversion losses increase proportionally. The transmission line losses increase when excess power is produced from the array when excess power is produced and when back-up from the grid has to be used.

Based on **Figure 32** and **Figure 33**, it can be said that in this case the optimal size of the array will be governed by the DC load which is the larger load for this operation. As depicted on **Figure 31**, which is a combination of both figures, the optimal size of the solar array is 1.25.

Figure 32 and **Figure 33** show the energy losses resulting from sizing the solar power plant to meet different capacity factors both the 90 MW DC and 30 MW AC output loads respectively. From these figures, when the solar power plant is designed at a capacity of 1.25 to meet 100 % of the load or an excess of 25 %, where the energy losses are at a minimum, beyond these factors, the losses increase exponentially when excess

electricity is generated from the plant. For the 90 MW DC load, the optimal size can be seen to be 112.5 MW DC output solar power plant and 37.5 MW AC for the 30 MW load.

5.2.2 Energy supply scenarios considered

The different scenarios considered are listed as follows:

- **Co-location:** Co-locating a solar power plant with the Skorpion Zinc Refinery.
- **Solar stand-alone:** This scenario considers a solar power plant located away from the Skorpion Zinc on a site which has a good solar radiation²¹. The Uppington area in South Africa is widely regarded as an ideal site. It has a better solar radiation than that at Skorpion Zinc. For this scenario, the conversion losses for the power generated from the solar power plant array are double because the DC electrical output generated by the array would have to be converted to an AC electrical output to suit the grid which only transmits AC electrical output. Before the power is used by the DC load, it would have to be converted back to DC electrical output.
- **Base case:** This scenario considers the current mode of power supply, from the conventional energy mix, with power transmitted over a long distance to meet the electricity demands of the Skorpion Zinc Refinery.

The losses incurred in each scenario arise from the transmission lines and the AC-DC or DC-AC conversion. These scenarios are presented schematically on **Figure 34** and **Figure 35**.

²¹ The solar radiation at Uppington is 6 % more than that at Skorpion Zinc. This is based on the comparison of the annual solar fraction for both sites

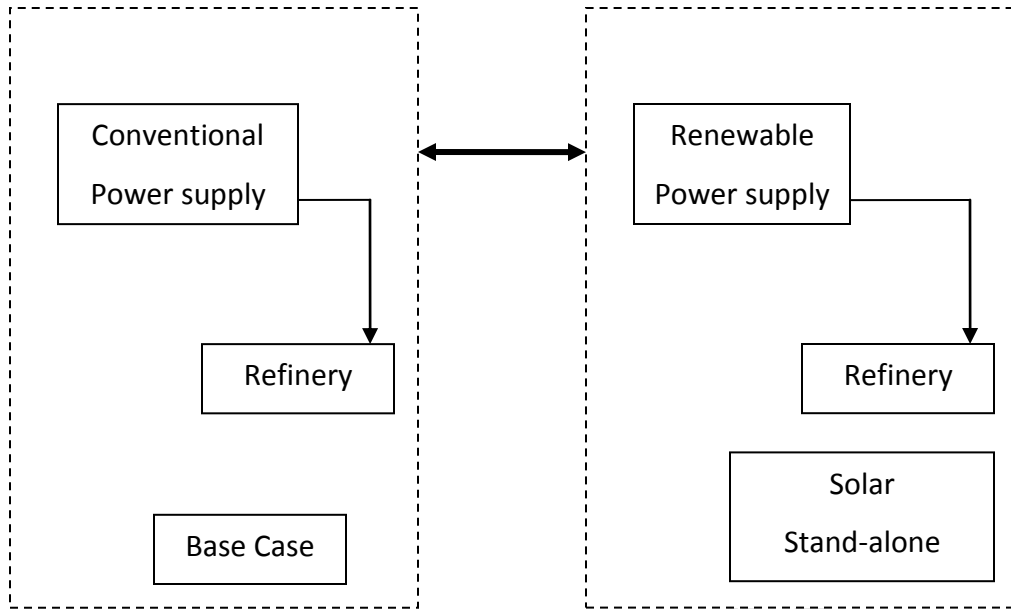


Figure 34: Schematic for the base case and solar stand-alone scenarios

5.1.4.1 Co-location case

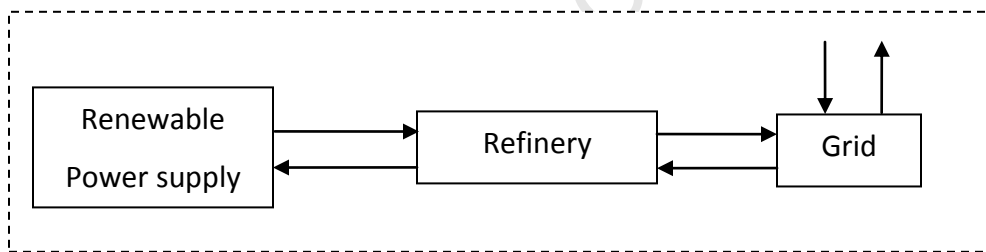


Figure 35: Schematic for the co-location case

5.2.3 Energy losses that could be avoided for each scenario of energy supply

The losses presented in this study refer to the energy losses evaluated in each scenario on an annual basis. In the case where the loss reduction from the base case is a negative value, this reflects an increase in losses above the base case scenario instead of a decrease.

The transmission line losses are very high compared to the AC-DC/DC-AC conversion loss for each scenario. This is because the grid is used in each scenario either as backup in the co-location and centralised scenarios and as a sole mode of energy supply in the base case. The long distance transmission lines on the grid exaggerate the transmission line losses. The conversion line losses are the highest in the centralised case because all the power produced from the solar array has to be converted from DC to AC output to suit the grid before it is transmitted. When this power reaches the refinery, some of it has to be converted to DC output to meet the DC load at the electrowinning circuits. The conversion losses for the co-location are incurred when power from the solar array has to meet the AC load and when excess power is generated from the array and has to be sent back onto the grid.

Table 32: Total annual electrical losses for each scenario

<i>Scenario</i>	<i>Total annual losses (GWh)</i>	<i>Reduction from base case</i>
Base Case	230.00	0%
Co-location	152.00	36%
Centralised at Upington	290.00	-3%

Based on **Table 32**, co-location a solar power plant with the Skorpion Zinc refinery results in a 36 % reduction in electrical losses from the base case scenario. A centralised solar power plant that is located at Upington results in an increase in the losses that are currently incurred in the base case scenario by 3 %. The next two tables (**Table 33** and **Table 34**) show how the transmission and conversion losses contribute to the reduction on increase of the overall losses.

Table 33: Annual electrical transmission losses for each scenario

<i>Scenario</i>	<i>Transmission line losses (GWh)</i>	<i>Reduction from base case</i>
Base Case	159	0.0%
Co-location	95	40.2%
Centralised at Uppington	148	6.8%

The transmission line losses are reduced significantly by 40 % from the base case scenario due to co-location. This is because with the use of a co-located solar array, less power is required from the grid and in the case where the array produces excess power during the peak hours, it is not as much as the power required when the sun is not available. This therefore reduces the power transmitted over the grid and the resulting transmission line losses. A centralised scenario results in a decrease in transmission line losses by 7 % from the base case scenario because the transmission line distance from Uppington to Skorpion Zinc refinery is 250 km less than the base case scenario and the backup power used when the sun is not available has to be transmitted over the same distance as for the base case scenario.

Table 34: Annual electrical AC-DC /DC-AC conversion losses

<i>Scenario</i>	<i>Conversion losses (GWh)</i>	<i>Reduction from base case</i>
Base Case	71	0.0%
Co-location	57	24.3%
Centralised at Upington	120	-28.5%

Co-location results in a 24 % reduction in conversion losses from the base case scenario whilst a centralised scenario results in an increase by 29 %. The reduction due to co-location is because a solar array produces DC electrical power directly and majority of the load requires a DC electrical input hence the reduction, the rest of the losses from conversion are due to DC-AC conversion required for the AC load and excess power generated from the array during peak hours of the day. When a solar power plant is in a centralised location at Upington, extra conversion losses are incurred because all the power has to be converted from DC-AC output before it is sent over the grid.

5.2.4 Analysis of expected solar power production

In this section, the expected hourly variation in power output from the solar plants is analysed. The hourly output from the solar power plants has been averaged on an annual basis. Since this does not give a good representation of the performance of the solar array, graphs showing the minimum (winter) and maximum (summer) values have also been presented. The results shown below include the overall solar power plant along with the DC and AC solar power plants separately since they meet different loads.

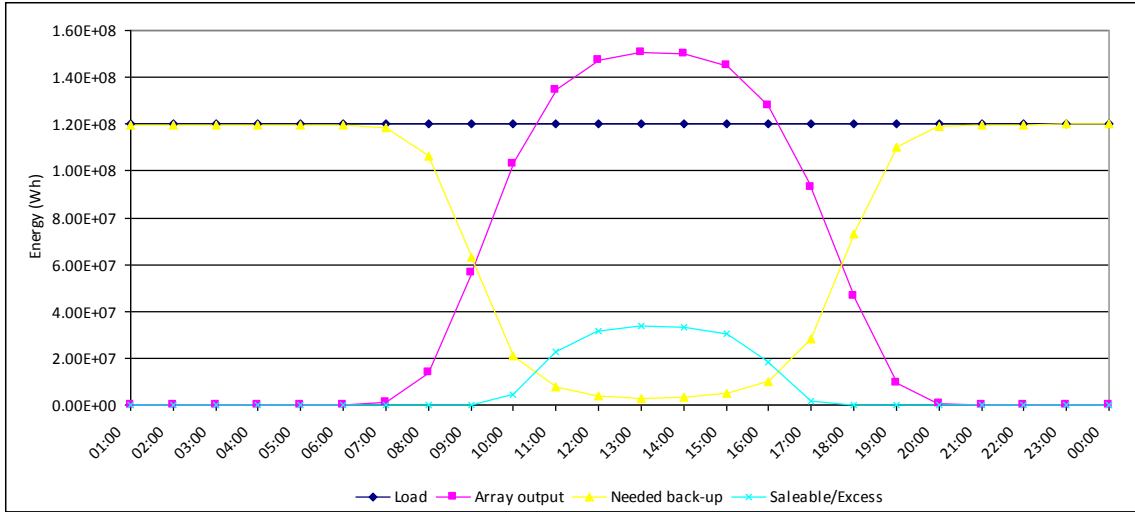


Figure 36: Schematic of the annual averaged load, array output needed backup and the saleable excess over a 24 hour period for the overall 120 MW load.

The array produces excess²² power between 10:00 and 16:00 on an average annual basis as shown on Figure 36. This time range varies during the different seasons of the year, but for an annual performance an average has been used.

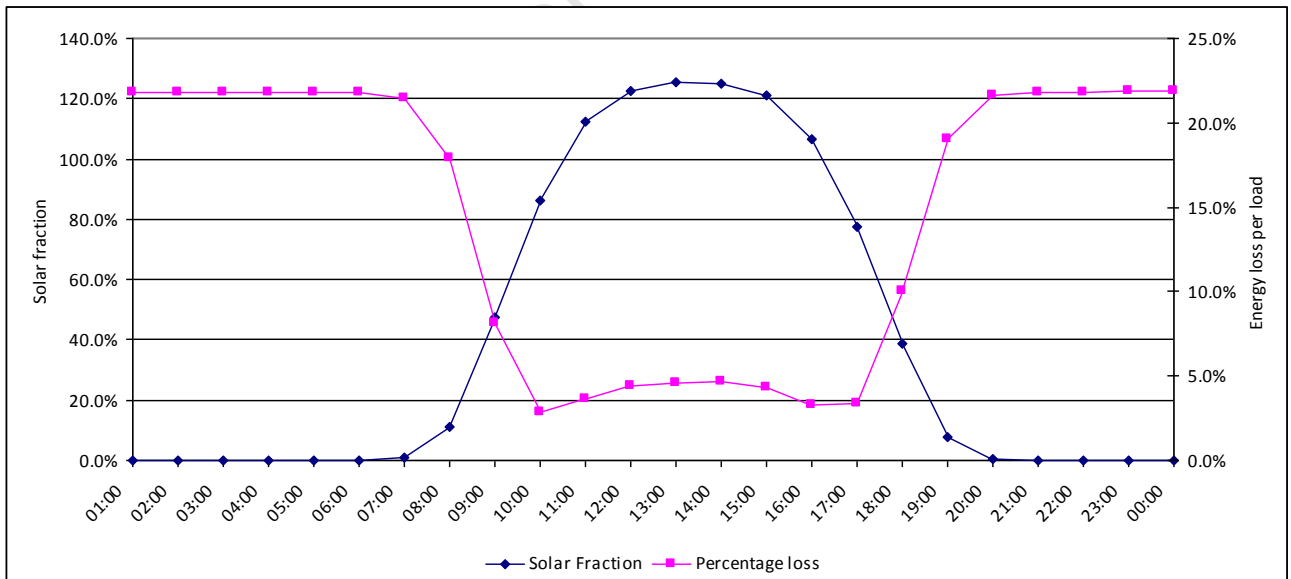


Figure 37: Schematic of the average annual solar fraction and energy loss per load for the overall 120 MW load over a 24-hour period.

²² More power than required by the load

The solar fraction²³ reaches beyond 100 % during peak hours as shown on **Figure 37**, at these times the energy loss per load increases because the excess power produced from the array has to be converted from DC-AC and sent back onto the grid where some of the produced power is also lost on the transmission lines.

5.2.4.1 Solar fraction for the 120 MW overall load

The solar fraction is the fraction of the load that is met by the solar power plant. At the times when the array generates excess power, the solar fraction is more than 100 %. **Figure 38** shows that during peak the solar fraction ranges between 95 % and 130 % throughout the year.

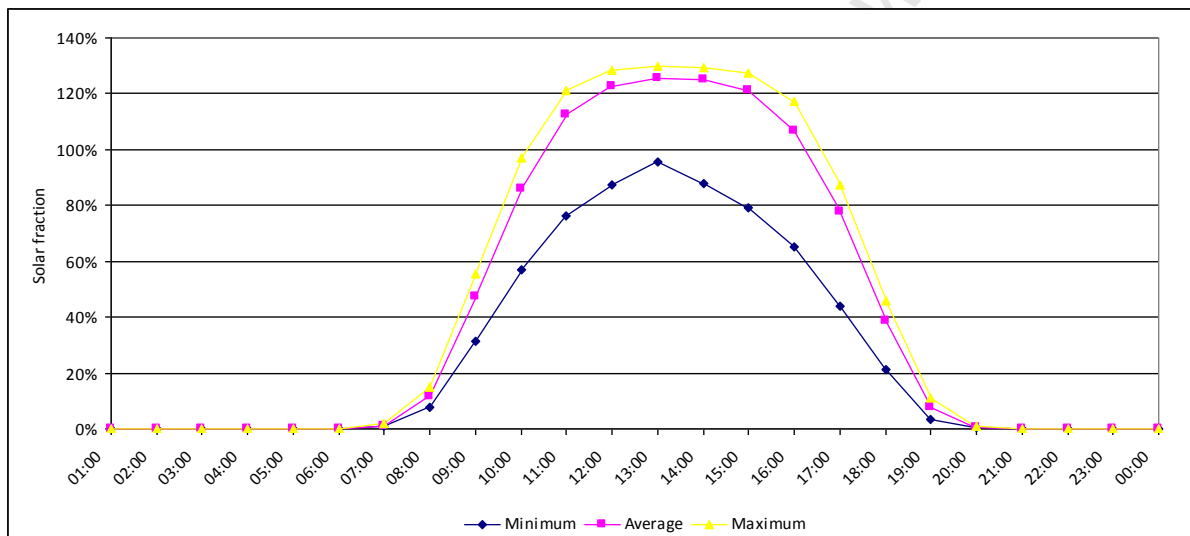


Figure 38: Schematic of the annual minimum, average and maximum solar fraction throughout a 24 hour period

5.2.4.2 Energy loss per 120 MW load

As already shown above, the co-located solar power plants generally reduce transmission and conversion losses for powering this remote metals refinery. Energy loss however increases somewhat when excess power is generated from the array between 10:00 and 17:00. The average loss per load decrease by between 77 to 86 % during these peak hours compared to the loss per load at the night time. **Figure 39** shows

²³ Percentage of the load that is met by the solar array

an increase in these losses during peak hours, this trend is mainly to the DC-AC conversion and transmission losses because whenever the solar array generates excess power, it has to be converted from the DC electrical output to an AC electrical output before it is sent back to the electricity grid sending power over the grid results in transmission line losses.

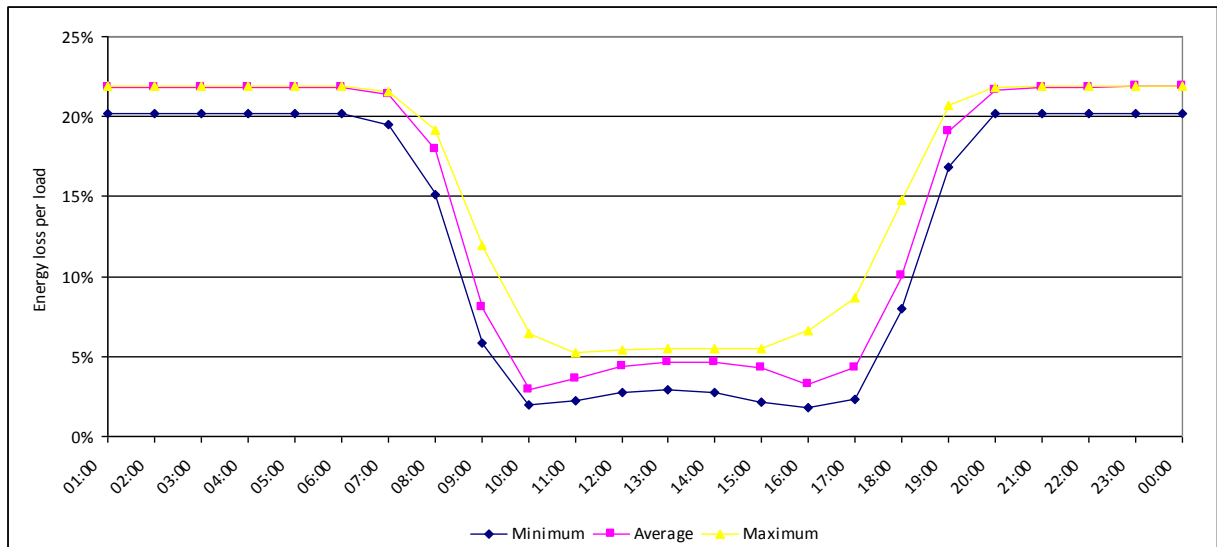


Figure 39: Schematic of the annual minimum, average and maximum percentage loss per 120 MW load throughout a 24 hour period

5.2.4.3 Array output for the overall 120 MW load

The array output is the power that the solar power plant produces. Considering that the plant has been designed to produce an excess of 25 % of the load, **Figure 40** shows that this excess power is produced between 10:00 and 16:00 during the sunniest days during the year. This figure also shows that between 12:00 and 15:00 the array is producing more power than it has been designed to produce because of the higher solar radiation at these times.

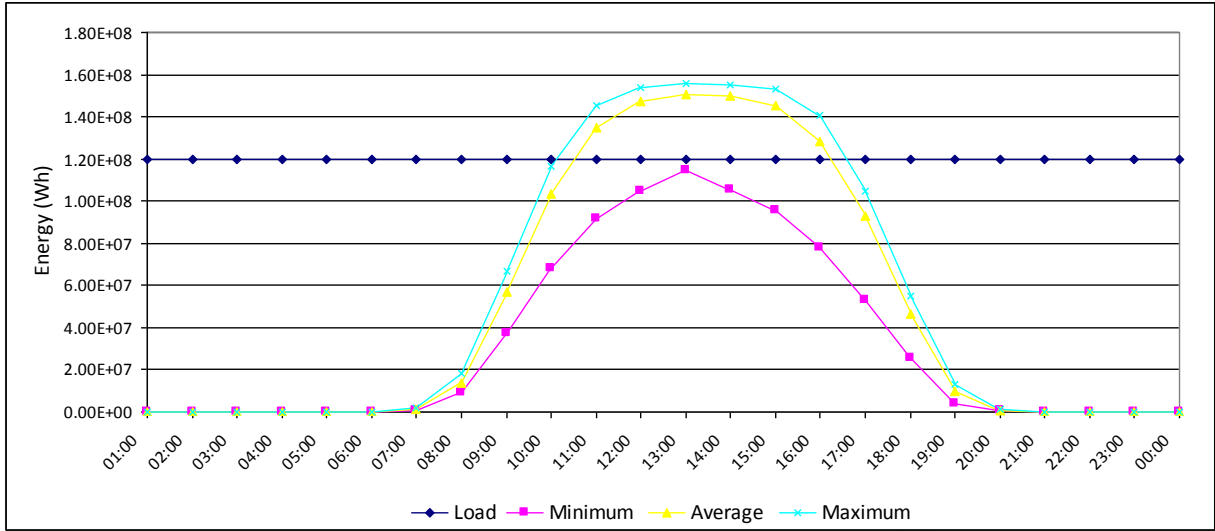


Figure 40: Schematic of the annual minimum, average and maximum array output (for a design load of 120 GWh used per hour)

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5.2.4.4 Backup required for balancing the load with power from the solar array

The refinery is already connected to the electricity grid; given the fluctuations in the solar-produced power, the grid would be used to supply the power that the solar array cannot supply. The back-up that the refinery required at different times of the day is presented on in

Figure 41 as minimum, average and maximum relative to the load. During the sunniest days, no backup is required from the grid; instead the array produces excess power.

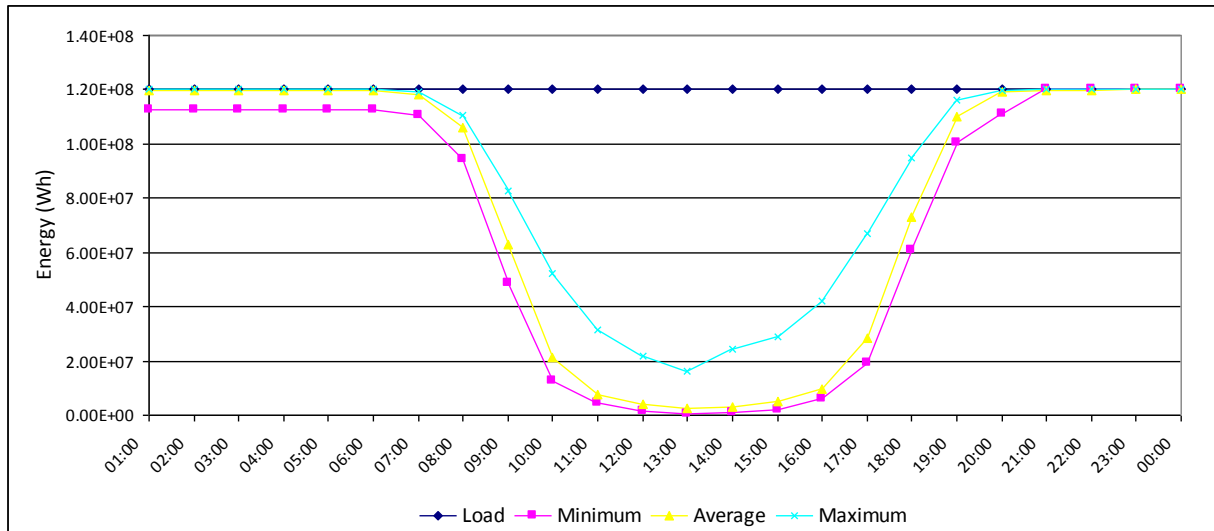


Figure 41: Schematic of the annual minimum, average and maximum needed backup to balance the load that cannot be met by the solar array

5.2.4.5 Excess power generated from the solar array

During the sunniest days, excess power is generated, this shows that if there are other energy consumers close to the solar power plant besides the refinery, they can also benefit from the use of the this excess power if they are also connected to the solar array. The array mostly generates excess power during peak hours which range between 10:00 and 16:00 as shown on

Figure 42.

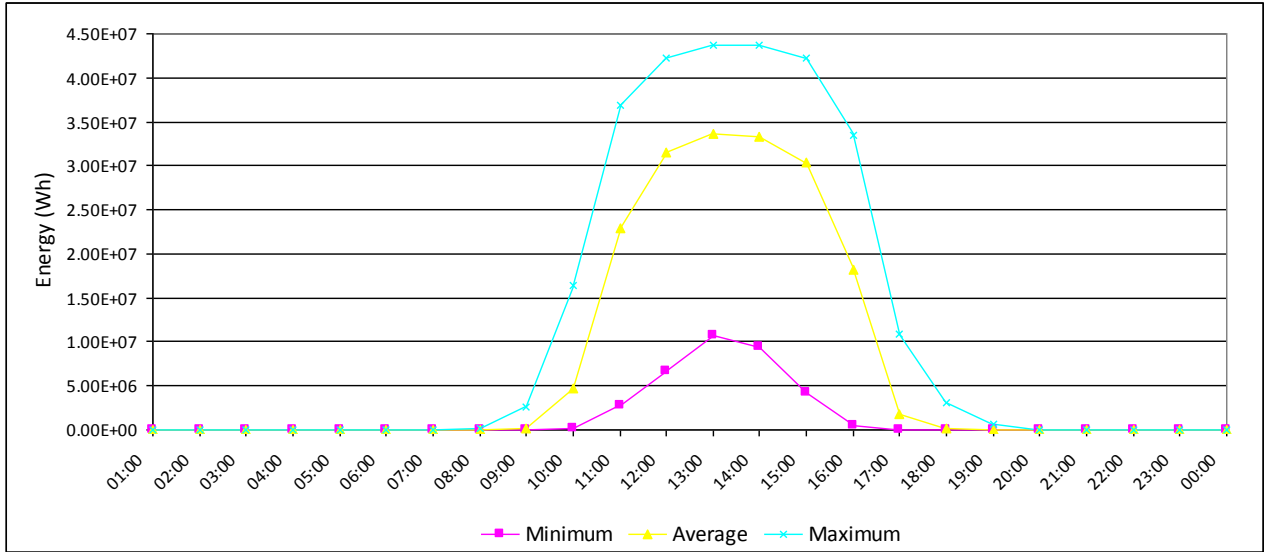


Figure 42: Annual minimum, average and maximum excess power generated from the solar array that is saleable

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Performance of the solar power plant designed to meet the 30 MW AC load

From Figure 43 , the AC load, the excess power produced is less compared to the load. This is because the power output from the array has to be converted to AC output and used by the load before it is available as excess power. Some of the power is also consumed by the inverters which form part of the load.

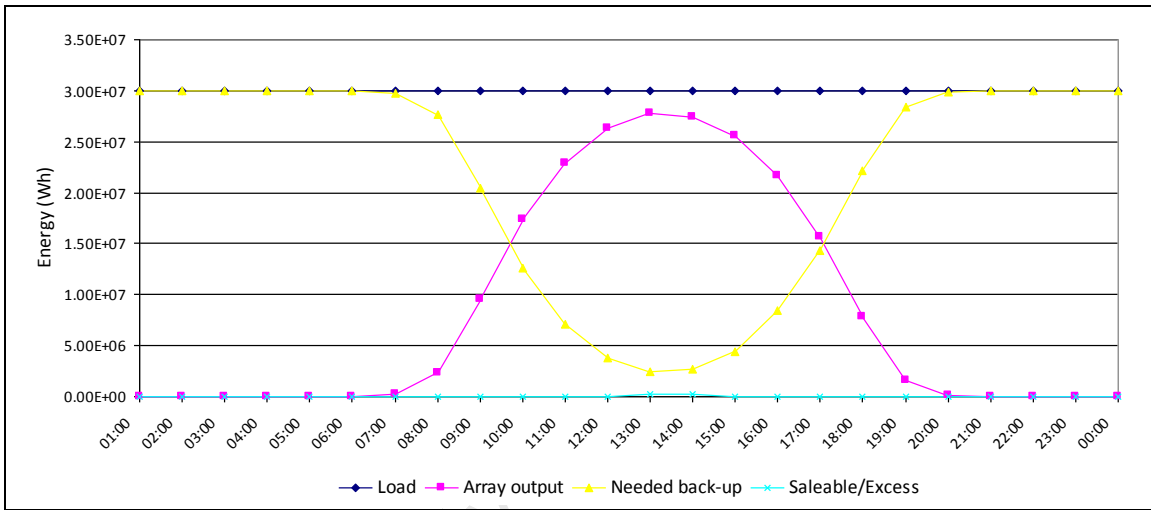


Figure 43: Average annual output from the solar power plant for the 30 MW AC load

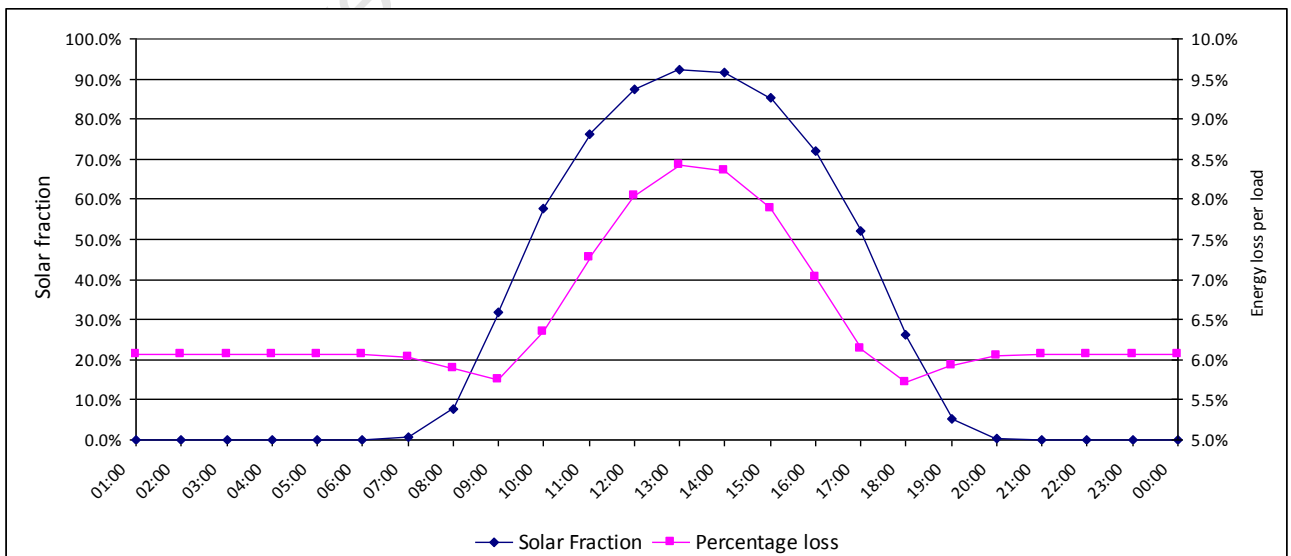


Figure 44: Average annual solar fraction and energy loss per 30 MW AC load

From Figure 44, the inverters also form part of the load. For this case, the energy loss per load increases as more power is produced by the array. The energy loss per load is directly proportional to the solar fraction and therefore depends highly on the amount of power that is produced from the array. The average annual solar fraction does not exceed 100 %, therefore the energy loss per load results from the DC-AC conversion losses.

5.2.4.6 Performance of the solar power plant designed to meet the 90 MW DC load

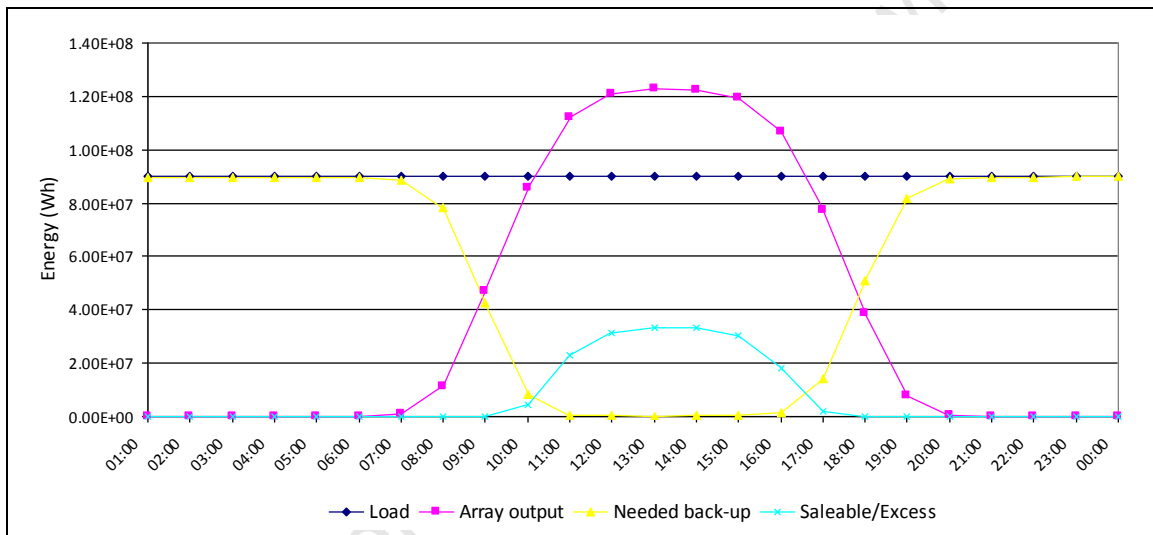


Figure 45: Average annual output from the solar power plant for the 90 MW DC load

Figure 45 show that on an annual average, for the DC load, excess power is generated between 09:00 am and 17:00. The DC power plant produces more excess power even though it is designed at the same capacity factor as the AC power plant, this is because the power produced from the array is used directly as it is produced and more power becomes available as excess after the demand for the load has been met.

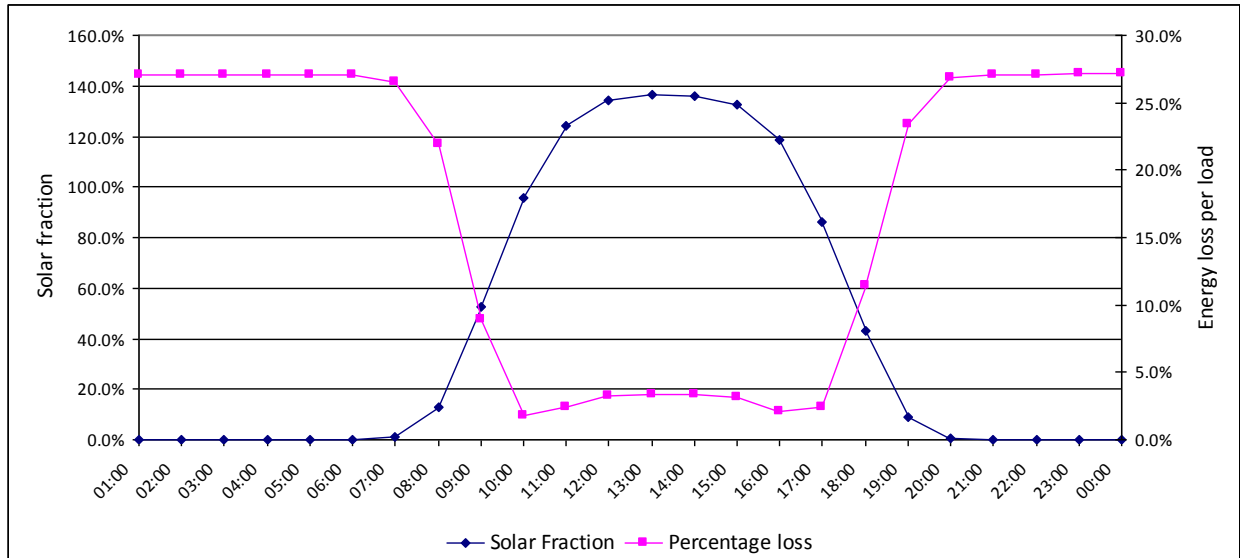


Figure 46: Average annual solar fraction and energy loss per load for the 90 MW DC load

From Figure 46, the energy loss per load decreases as the solar fraction from the power plant increases, but when this solar fraction exceeds 100 %, the energy loss per load increases because of excess power that has to be sent back to the grid. This is attributed to the fact that when excess power is generated, it has to be converted to AC output to be compatible with power on the grid before it is sent through to the grid and transmission line losses are also incurred when power is sent over the transmission lines. These losses drop to a range of 79 to 87 % between 10:00 and 17:00 from the energy loss per load at night when the array is not reducing any power.

5.2.5 Power output profile vs. load profile

It has been assumed that the load profile at Skorpion Zinc is flat with little or no fluctuations. Due to the intermittency of the sun, the power output profile is not flat; instead it follows a concave parabolic profile from the time when the sun rises, to the time when it sets. Since this is a grid-connected orientation, the excess power generated from the power plant is sent back to the electricity grid. For a grid connected operation, the unstable profile of the power output from the solar power plant is not an issue, because the grid is available to balance the deficit and take the excess produced by the solar power plant. In the case of Skorpion Zinc, backup power will be required early and

late in the day, and especially at night. There is excess generation capacity available on the Southern African electricity grid at night, but power availability in the morning and evening peak periods is more problematic.

5.3 Discussion

Power consumers only pay for the power that they receive at their location. A large power consumer that is located away from the electricity grid is not liable for the transmission line losses that are incurred when this power is transmitted and distributed to them. An operation such as the Skorpion Zinc would not be responsible for the transmission losses, instead they only have to account for the power that they use and the losses incurred when converting power from AC to DC. The power utility is accountable for the power lost due to long distance grid connections. It can be said that co-locating a solar power plant with a large energy consumer would benefit both the utility company as their transmission losses would be reduced and the power consumer as their AC-DC conversion losses would also be reduced. Generating excess power by means of a DC power plant results in conversion losses which increase as more excess power is generated. This is attributed to the fact that the power generated has to be converted from DC to AC electrical output. Generating power for a DC load using solar PV power plant results in more gains than losses because the power can be used as it is. In this study, the results show that having a power plant located away from the load would result in more power being lost than it would be if a solar power plant of the same magnitude were co-located with the large power consumer.

5.4 Concluding remarks

This Chapter has demonstrated that solar energy results in more gains when a solar power plant is co-located with the load compared to when the same power plant is located away from the load. It has also shown that harnessing solar energy by a PV installation to meet the demands of a DC load is more beneficial than meeting an AC load because most of the losses resulting from inverting can be avoided. Sizing the solar

array to meet the demand of the load also forms an important part of setting up a solar power plant. In this case, to minimise the overall losses resulting from both AC-DC/DC-AC conversion and transmission losses, the optimal capacity of the array is at 25 % above the load. This may be different in other cases depending on the kind of losses incurred and the overall objective of setting up the array and the load profile as well.

These results make it clear that if there are plans of using solar power at a utility scale, serious consideration should be given to a co-located installation. The transmission line energy losses remain high compared to the AC-DC or DC-AC conversion losses. From this, it can be deduced that instead of transmitting power over a long distance, a mini-grid next to the refinery can be used to avoid losses. The excess power generated from the solar array could also be used to supply power to the neighbouring communities instead of sending power back onto the grid over a long distance.

Chapter 6 CONCLUSIONS AND RECOMMENDATIONS

This dissertation investigated the use of solar energy in the minerals processing industry, in particular for operations that are located in remote areas and how they would benefit from the use of solar energy for electricity generation with focus on the reduced energy dependence from their current fossil based energy supply with co-locating a solar power plant. This Chapter synthesises the findings presented in the previous chapters relative to the aims, key questions and hypotheses. Conclusions are drawn from these findings and recommendations are made based on these conclusions.

6.1 Conclusions

The following subsections develop the conclusions drawn from this study.

6.1.1 Review of research motivation

This study was motivated by the fact that the global climate crisis is imminent and there is a need to explore renewable fuels and those end-use energy products from the sun such as electricity and steam can be generated at a utility scale. It was also noted that there are currently no published studies about these solar energy innovations and how they can be used for the energy intensive minerals processing industry. However, this industry can reduce its energy related carbon footprint by exploring renewable energy sources to supplement their energy demands. This study has demonstrated that for the selected operations solar energy can be used to supply 100 % of the electricity required or more when solar radiance is at its peak. There is also a potential to meet some of the thermal energy demands during the day when the sun is available which could also be extended to night-time hours via the use of thermal storage systems. The use of solar energy in conjunction with conventional energy would contribute in mitigating the impact of fossil based fuels on the global climate crisis that we are currently faced with.

6.1.2 Objectives of research and major findings

This study was aimed at addressing the following objectives:

- i. **Analyse typical energy needs on a minerals processing plant against the background of current and emerging solar energy technologies, climate change mitigation pressures and sustainable energy supply.** An energy analysis was conducted for each of the five chosen operations based on their process flowsheets, as presented in Chapter 4. This analysis was used to establish the type of loads that these operations have and their respective capacities. This information was used in conjunction with the solar energy harnessing technologies presented in Chapter 2 to evaluate which one could be used to meet the energy demands of these operations.
- ii. **Quantify environmental gains to be made by such contending solar energy technologies if applied in the minerals industry.** Avoidable energy losses were used as a proxy for environmental gains. These were found to be transmission line losses, AC-DC conversion losses and fuel consumption due to inefficiencies as presented in Chapter 4. They were quantified on the sole basis on co-location a solar power plant with a minerals processing operation. A reduction in these losses would result in less conventional energy being consumed.
- iii. **Determine how the use of solar energy at utility scale on the site of a minerals processing industry would first be attractive compared to the fuels that are currently being used to satisfy the energy requirements of this industry.** This was achieved by considering different scenarios of using solar energy for power generation in the minerals processing industry and establishing the extent to which the use of solar energy can reduce the electrical losses incurred in the current mode of power supply. This is presented in Chapter 5 where it was shown that an operation with a high DC electrical input load would benefit from co-locating a utility scale solar PV plant with their operation. Furthermore, it was also found that

operations that are located in remote areas away from the electricity grid could reduce their transmission losses when co-located with a solar power plant as witnessed in the Escondida operations and Skorpion Zinc Refinery.

6.1.3 Conclusions drawn from literature

Renewable energy options such as solar energy have been labelled as a sustainable form of supplying energy compared to most of its non-renewable energy counterparts, but the obstacle that many decision makers face is that power generated from these renewable fuels remains costly compared to fossil generated electricity. It was shown that there has been a significant decrease in the cost of producing solar energy end products and most of these technologies are not as expensive as they used to be due to economies of scale and learning curves. Although solar electric systems remain costly relative to conventional fossil fuelled electric systems, different factors such as high electricity rates, high insolation levels and good solar radiation make it competitive.

Although solar energy is seen as a good form of generating electricity, when it is used for a large energy consumer as the minerals processing industry, measures which may sometimes involve fossil generated electricity should be in place for continuous supply since the sun is intermittent. Solar thermal power plants can replace conventional thermal power plants - and without any qualitative change in the grid structure. Due to the option of thermal storage, the turbines of solar thermal power plants can also produce power in low-radiation periods and at night also when combined with conventional thermal power plants which are fired by fossil fuels. Grid connected systems have shown to be the best option in ensuring continuous electricity supply for solar PV system. Although systems with a battery-based storage are a reliable source of electricity and provide emergency power during a utility outage, they remain more costly and less efficient than battery-less systems.

Most operations in the minerals processing industry are large energy consumers with a high energy carbon footprint. In this day of limited natural resources that are used for

energy generation and their contribution to the global climate change crisis, it is crucial that this industry moves from conventional energy sources and seek alternatives to change its notorious environmental legacy. An analysis of energy use in mineral processing and established electricity usage high, this electricity is used as AC and/or DC electrical output. Diesel consumption is also high and mainly used for electricity generation. Steam is one of the energy products that are required in some of the processes.

Long distance transmission networks present a challenge of intensified transmission line losses; therefore these industries can explore ways of reducing these. Also many of the metals refineries require DC electrical output as their major form of electrical energy, instead of the conventional AC electrical output that is supplied by the electricity grid that they are currently using. These operations thus make use of rectifiers to convert the AC electrical input to DC electrical output which would then be a useable energy product for their processes and this introduces conversion losses.

6.1.4 Validation of hypotheses

Two hypotheses were formulated at the start of Chapter 3. This subsection evaluates how the assembled evidence supports these hypotheses.

The load pattern i.e. the nature of larger power requirements of a minerals processing operation relative to the existing energy infrastructure will dictate how attractive co-located solar energy provision through competing technological options will be.

A qualitative assessment of all the operations was conducted to evaluate the best option for co-location with the selected operations between CSP and PV based on the available infrastructure and power requirements of these operations.

This was followed by a preliminary solar power plant was designed and co-located with all the selected sites. These indicated how co-location affects transmission line losses and AC-DC and DC-AC transmission line losses. The results show that co-location is attractive for four of the five operations studied. It also was shown that for operations with an AC load only, solar thermal technologies would be more attractive because the DC-AC conversion losses that are incurred when solar PV technologies are used to supply power to an AC load will be avoided.

Etango Uranium uses diesel generators for electricity supply, with the fluctuating diesel prices, inefficiencies along with pollution²⁴ associated with these generators; the use of solar for power generation seems viable for this operation since it has a very good solar resource and dry conditions. CSP was the preferred technology for this operation but the shortage of water in this area makes it unattractive leaving PV as the next option. When solar PV technology is combined with diesel generators for power generation, the fuel consumption from power generation can be reduced.

RBMR is located close to the electricity grid and most of the power used for this operation consumed in the Electrowinning circuit. Both CSP and PV are attractive for this operation and would require a detailed comparison to select the best option. Solar PV technology can be used to supply power to these circuits while the rest of the plant is supplied by the excess power²⁵ generated from the solar array along with the grid which could also be used as a form of backup for the electrowinning circuits. This would reduce the AC-DC conversion losses that this operation is currently experiencing and would also reduce the transmission line losses during the daytime when the array is producing power.

²⁴ Noise and environmental pollution

²⁵ If the array is designed to produce excess power, this power can be used on the other parts of the plant that are not supplied by the solar array during the peak hours.

MMC is also located close to the electricity grid and power stations that generate electricity. None of the options are attractive for this option as the reduction in conversion losses, transmission line losses are insignificant. This operation does not have enough space to accommodate a utility scale solar power plant. If there was enough space, a solar power plant would be used to supply power to the electrowinning circuit while the rest of the plant uses power from the grid as is the case for the RBMR.

Escondida copper operations are located away from the electricity grid and depend on independent power producers to supply them with electricity. For the concentrators which have a 100 % AC demand, CSP is the preferred technology but shortage of water in this area is an obstacle for this option. Both CSP and PV are attractive for the sulphide and oxide ore flowsheets. These operations would benefit from the use of for using solar PV technologies to meet their energy demands since they are located in an area which has one of the best solar resources in the world and depends mostly on fossil fuels for power generation which are impacting negatively on the carbon footprint of their mining and beneficiation operations. The solar arrays for each of the operations would supply power for the overall load at each operation and the excess power generated during the peak hours can be sent back on to the grid and distributed to other consumers on the transmission network.

The use of PV solar power on a high DC load with co-location will see a significant reduction in transmission line losses and DC-AC conversion losses compared to locating PV solar in a location with the best solar resource away from the load. For differences less than 25 % in the quality of the solar resource, the avoided conversion and transmission line losses from co-location would make this a preferred investment option over a stand-alone large PV plant.

A hypothetical solar power plant was designed and located at Upington which is the closest location with a good solar resource after Rosh Pinah where the Skorpion Zinc Refinery is located.

The findings of locating a solar power plant in a centralised location away from the electricity grid show a reduction in the transmission losses from the base case by 7 % from the base case and the conversion losses increase by 28.5 %. This confirms this hypothesis. The results of this study further show that a solar PV power plant located away from the load would result in more power being lost due to both transmission and conversion losses than if the plant of the same magnitude were co-located with the large power consumer.

Producing excess power from a PV solar array results in DC-AC conversion losses as the power has to be converted from DC to AC, therefore the optimal size of the array becomes crucial. Generating power from a solar PV for a DC load results in no conversion losses when the array produces enough power to meet the load without excess as the array produces DC power directly.

6.1.5 Summary of key conclusions

The following key conclusions formulated based on the results of this study.

- i. The utility company transmitting power to large energy consumers over a long distance transmission network is responsible for the transmission line losses and the consumer with a DC load is responsible for the AC-DC conversion losses. Therefore co-locating a PV solar power plant with a large power consumer would benefit both the utility company and the consumer with a DC load as the transmission line losses would be reduced and AC-DC conversion losses would be avoided respectively.

- ii. Chapter 5 demonstrated that conversion losses can be avoided by co-locating a solar power plant with a minerals processing operation and the transmission line losses can also be reduced during the daytime when less power is transmitted over the grid to meet the deficit that the solar power plant cannot supply. The studied cases show that even when there is a big DC load, the magnitude of avoidable transmission losses is greater than that of avoidable conversion losses. This is more apparent for the remote operations.

6.1.6 Limitations on findings

One of the major assumptions made when designing the solar power plants was that load follows a flat profile. Most operations have varying throughput rates throughout the year and sometimes also throughout the day. When this is accounted for in a real situation, these fluctuations in the load profile could affect some of the findings presented in this study.

6.1.7 Outcomes achieved

This thesis has achieved the following outcomes:

- i. Characterised the energy requirements of selected typical flowsheets in the minerals to metals processing industry.
- ii. Established the extent to which solar energy can replace energy usage in this industry.
- iii. Shown that there could be significant synergistic energy efficiency gains for the use of solar energy by some minerals processing operations.

6.2 Recommendations

The following subsections present the recommendations that are formulated based on the conclusions made in the previous section.

6.2.1 Recommendations directed at those intending to use solar energy for minerals processing applications

- If an operation is located away from the electricity grid, the cost, environmental impact and transmission line losses that are associated with grid extension should be taken into consideration. The utility company could give an incentive to large energy consumers who co-locate a solar PV power plant with their operations.
- Existing operations with a high DC load (as found esp. in electro-winning circuits) should consider adding a solar PV plant to offset some of their day-time electricity demands. This would result not only in a reduction of AC-DC conversion losses; avoided transmission line losses can be larger, depending on the distance from the nearest power producer.
- A qualitative analysis has shown that CSP is the preferred technology for operations with a 100 % AC load. Operations with a pure AC load, such as concentrators, should consider co-located CSP plants, possibly with thermal storage, esp. when they are far from the grid and in areas with high direct solar insolation. This incentive becomes even bigger when they have a thermal energy demand too.
- For new operations with a high DC load where a decision on the mode of power supply is still under discussion, the comparison between co-locating a solar power plant should take into consideration the cost of setting up and maintaining the infrastructure required such as rectifiers. When electricity has to be converted from AC to DC electrical output, the conversion losses should be considered. The sizing of the solar array becomes important and the optimal size should ensure that that the transmission line losses and DC-AC conversion losses are minimised if the array generates excess power.

6.2.2 Recommendations for further research

The following are key recommendations for further research in this study

- A quantitative avoidable energy loss comparison resulting from CSP plants was not done in this study. Such a study would be useful for those cases in this study where the qualitative comparison with PV was inconclusive (viz. RBMR, Skorpion Zinc, Escondida refineries).
- The avoidable energy loss estimations done in this study do not yet provide sufficient information to build a financial case. It is therefore recommended that a financial analysis be done, in the first instance for the Skorpion Zinc case, building on the PV plant design and analysis presented here. Such an analysis should incorporate environmental tax levies such as carbon taxes on fossil generated electricity and should also consider to whose account the avoided transmission and conversion energy losses would accrue.

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APPENDIX

I. Appendix A: Water use for CSP vs Water use in typical minerals processing operations

Table 35: Typical ore grades at minerals processing operations

Ore type	Grade (%)
Base(Low grade)	0.1 - 5
Ferrous(High grade)	30 - 65

Correlation by Norgate and Lovel (Bhikha, 2009) is used to estimate water consumption:

$$W = 167.7 G^{-0.9039}$$

Where

W = water consumption (m³/ton metal refined)

G = grade of ore (% metal)

Based on the correlation and Table 35, the water consumption results presented on Table 36 were developed

Table 36: Water consumption at typical minerals processing operations

Base(m ³ /ton)	1 344.1 - 39.2
Ferrous(m ³ /ton)	3.9 - 7.8

Table 37: Typical energy consumption in the minerals processing industry (Eoearth,2012)

	Energy consumption (MWh/ton)
Base	0.0000179 - 0.0000252
Ferrous	0.7 - 0.8

Table 38: Water consumption at minerals processing operations due to CSP technologies(US DOE, 2009)

CSP technologies	Base metals(m ³ /ton)	Ferrous metals(m ³ /ton)
Power Tower	143 803 - 163 734	3.68 - 5.16
Parabolic	206 822 - 199 485	5.29 - 6.28
Dish Engine	4 229 – 3004	0.09 - 0.11
Fresnel	211 475 - 150 215	4.73 - 5.41

II. Appendix B: Energy mix for the countries

Table 39: Data for Chile-Atacama/Antofagasta area (Speiser, 2008)

Type	Capacity(MW)	% Contribution
Coal	1466	46.79%
Oil	225	7.18%
Natural Gas	1395	44.53%
Diesel	47	1.50%
Total	3133	100.00%

Table 40: Data for Chilean energy mix (Speiser, 2008)

Type	Capacity (MW)	% Contribution
Hydro	4130	42.58%
Coal	3436	35.42%
Natural Gas	1955	20.15%
Diesel	179	1.85%
Total	9700	100.00%

Table 41: Data for Namibian Energy Mix (De Vita, Endresen & Hunt, 2006)

Type	Capacity (MW)	Contribution %
Hydro	240	63.16%
Coal	120	31.58%
Diesel	20	5.26%
Total	380	100.00%

Table 42: Data for South African energy mix (ESKOM, 2002)

Type	Capacity(MW)	% Contribution
Coal fired	32066	88.56%
Gas turbine	342	0.94%
Hydroelectric	600	1.66%
Pumped storage	1400	3.87%
Nuclear	1800	4.97%
Total	36208	100.00%

III. Appendix B: Data used for the energy inventory and process description of flowsheets

IV. Etango Uranium

Process description for Etango Uranium

The following paragraphs give a detailed description of the refinery's process flowsheet shown on Chapter 4. Run of Mine (ROM) ore is supplied directly to the primary crushing circuit where it is crushed and classified. The crushed ore from the Gyratory crusher is fed to the SAG milling circuits where the ore is milled under acidic conditions. The Comminution circuit which includes: Classification, Gyratory crusher and SAG milling has a total power capacity of 18 MW. Crushed ore is leached under atmospheric conditions and room temperature in mechanically agitated tanks. The resulting slurry from the leach circuit is pumped to belt filters for solid liquid separation and to maximise the separation of the uranium bearing liquor from the leach solids. The pregnant leach solution is pumped to the solvent extraction circuit for solution purification and concentration. The loaded organic from the extraction circuit is transported to the organic scrubbing circuit, where deionised water is used to remove silica and ferric iron. The loaded aqueous from the solvent extraction circuit is sent to two precipitation tanks where ammonia gas is added to produce ammonium diuranate (ADU) precipitate. This precipitate gravitates to the precipitation thickener where the solids are concentrated. The thickener underflow is pumped to the centrifuge circuit which is designed to further concentrate the solids and also wash the ADU stream. The centrifuged ADU slurry is pumped to the calcination unit for conversion to uranium oxide. This is achieved by oxidation at a temperature of 800°C to 850°C in a rotary kiln. A drumming facility is employed for safe packaging of the final product. This part of the refinery has a power capacity of 12 MW.

Table 43: Etango Uranium (Inwood, 2008)

Electrical Capacity (MW)	30
Ore processed (ton/annum)	1.50E+07
U ₃ O ₈ Production (ton/annum)	2900 to 4000
Ore type	Alaskite/ Alkaline

Table 44: Available resources (Inwood, 2008) and (Bannerman, 2007)

Resource reported at lower cut-off of 100 ppm U ₃ O ₈ : (Mt)	120.7
Grade(ppm)	235
	197
	209
Estimated lifetime	12 to 25 + years

Table 45: Energy consumption data (Inwood, 2008)

Comminution	
Impact Crushing Index(kWh/ton)	8.7
Crushing capacity(MW)	24.8
360 days operation(MW)	15.1
Average Work Index	
Rod Mill(kWh/ton)	12.3
<i>Rod mill capacity(MW)</i>	35.1
Ball mill(kWh/ton)	14.3
<i>Ball mill capacity(MW)</i>	40.8
<i>360 days operation(MW)</i>	24.8
Crushing and Stockpiling	
Rate of Crushing(ton/hour)	2854
Stockpile Capacity(ton)	35000
Stockpile live capacity(Hour)	18
Stockpiling rate(ton/hour)	1944
Grinding/Milling	
SAG mill capacity(MW)	18
<i>SAG mill work index</i>	
<i>calculated(kWh/ton)</i>	6.31
<i>based on 360 days operation(kWh/ton)</i>	10.4

Assumptions: The actual operation has been reported as 219 days per annum instead of a 365 day operation. An operation time of 360 days per annum has been used to

reconcile the calculations since the 219 days is not consistent with the other published reports which use 360 days instead.

Table 46: Operating conditions at the leach tanks (Inwood, 2008)

Temperature(°C)	30
Minimum particle sizes (µm)	425
Maximum particle sizes (µm)	1300
P ₈₀ size (µm)	710
Number of tanks	6
Mode of mixing	Mechanically agitated
Operating volume for each tank(m ³)	2250
Leach residence time(hours)	14
Specific gravity(ore) (ton/m ³)	2.6
Density of H ₂ SO ₄ (kg/m ³)	1841
Slurry density(solids) %(w/w)	60
Slurry density(liquid) %(w/w)	40
Density of Slurry mixture(kg/m ³)	2231.931362
Volume occupied by slurry mixture(m ³)	13500
Mass of slurry mixture(ton/h)	2152

V. Skorpion Zinc

Process description for Skorpion Zinc

The Skorpion Zinc Refinery has several major plant sections which are listed and discussed as follows:

Comminution: There are two input streams are the Zinc ore and the limestone streams. The zinc ore and limestone are crushed to about 8 mm and 10 mm respectively. The ore is then fed into a stacker reclaimer unit for blending while the limestone is conveyed into the silo. From these storage places, the streams are both fed forward into separate mills where they are each milled to size. The products are then thickened for feeding into the leach and neutralisation circuits respectively. The residue from the refinery process is sent by a conveyor belt in a cake form to the tailings dump some 3 km away.

Leaching: The milled and thickened ore product from the Comminution is sent to a leaching circuit where sulphuric acid is added to primarily dissolve the Zinc.

Neutralisation: The neutralisation circuit follows where milled and thickened limestone is added to precipitate some of the dissolved impurities in the leach circuit. **Thickening:** The resulting slurry is then thickened and the underflow solids are sent to the residue belt filters. The overflow solution containing Zinc pregnant leach solution (PLS) is fed to the solvent extraction circuit. The Cu/Ni cementation circuit receives a portion of the PLS and uses zinc dust to remove the contained copper. **Filtration:** The slurry (underflow) from the thickening circuit is filtered here using belt filters. The residue belt product is a relatively dry cake which is sent to the tailings dump. The residue belt remnants solution reports to the basic Zinc sulphate (BZS) circuit. **BZS precipitation:** This circuit forms a BZS precipitate by adding limestone. The BZS is formed and re-sent to the leach and the zinc free solution is reused. **Effluent treatment plant:** This circuit receives plant spillages and precipitates the metals to produce a solution for reuse in the plant. **Solvent extraction:** The PLS from the leach is treated in a aqueous/organic set of circuits through mixer settlers where the first circuit extracts the Zinc from the aqueous to the organic phase. The Zinc diminished solution is re-sent to the leach to precipitate more Zinc. **Washing:** The second circuit both chemically and mechanically washes the impurities out of the solution and ensures that a clean solution is conveyed to the third stripping circuit. **Stripping:** An electrolyte is used to strip the Zinc off the organic into an acidic Zinc solution called loaded electrolyte. **Regeneration circuits:** Hydrochloric acid is used to regenerate the organics which are re-used. A reverse osmosis mechanism is used to provide demineralised water. **Electrowinning:** This section uses electrical power to plate Zinc out of the loaded electrolyte solution onto solid cathodes. Cathodes produced are of special high grade quality (99.995 pure Zinc). **Cast house:** The Zinc cathode sheets stripped out of electrowinning are fed into melting furnaces. From here ingots or jumbo forms are cast for sale to the international markets. The Zinc products are transported by truck to Luderitz where they are stored before they are shipped.

Table 47: Boilers at Skorpion Zinc (Bateman Engineering, 2000)

Capacity	14 MW
Energy Type	Steam
Method of generation	Sulphuric acid plant or Electrodes

Table 48: Electrowinning circuit (van Dyk, 2001)

Electrical Capacity(MW)	90 DC electrical input	
Zn cathodes production capacity(ton/annual)	150000	
Comparing design and operating values	Design	Actual
Energy consumption for Zn EW(kWh/ton)	3400	3060
Energy consumed for Zn produced(MWh)	510000	459000
Time required for plating per annual(Hours)	5184	5184
EW electrical capacity(MW)	98	89
<i>Validating results (Using an average)</i>		
Energy consumed per Zn produced(kWh/ton)	3190	
Deviation	183	

Table 49: Energy consumption from Comminution to Solvent extraction units

Electrical Capacity (MW)	30 AC electrical input	
Comparing design and operating values	Design	Actual
Ore processed(Ton/annum)	1.50E+06	variable
Processing time per annual(hours)	8640	N/A
Energy consumption per ore(kWh/ton)	172.80	170

Table 50: Operating conditions for the Electrowinning circuit (Sole, Fuls & Gnoinski, 2009)

Parameter	Skorpion's operation
Current density(A/m ²)	400-428
Cell voltage (V)	3.2
Energy consumption (kWh/ton DC)	3060
Current efficiency (%)	89-93
Anode composition	Cast Pb 0.5 % Ag
Stater cathode composition	Aluminium
Cathode area(m ²)	3.6
Mn(g/L)	3
Licorice(g/L)	14.6
Arabic gum(g/t Zn)	27
SrCO ₃ (g/ t ZN)	975
Plating cycle (days)	2
Temperature	39

VI. Manganese metal company

Process description for MMC

The extraction process begins with high-grade ore, mined in the Kalahari. The ore is milled to a powder before reducing it into a soluble form in rotary kilns. The reduced ore is dissolved in an acid solution followed by purification (precipitation of impurities and filtration). Sulphur dioxide, and not the selenium dioxide, is added to the purified solution before electrolysis can take place. The solution is then fed into the electrolytic cells where electric current causes the manganese to plate on the cathodes, while the sulphuric acid formed at the anode is recycled back to the dissolution process. The plated manganese is stripped from the cathode, washed, dried and degassed. This represents manganese in its purest form. Depending on the process requirements, the metal is then processed further and packaged for shipment.

Table 51: Process production data (Duan and others, 2010)

Mn produced(ton/annum)	28000
Ore consumption(ton ore/ton Mn)	2.67
Ore consumption(ton/annum)	74760
Mn ore content(%)	44
Product purity(%)	99.9
Current passed through cellhouse(A)	56000

Table 52: Electricity consumption (Duan and others, 2010)

Parameter	Cell House	Overall plant
Electricity consumption(kWh/ton Mn)	2100	6800
Electricity consumption(kWh)	58800000	1.9E+08
Power capacity(MW)	6.71	21.74

VII. Rustenburg's Base Metals Refinery

Process description for the RBMR

The leach circuit is comprised of: Copper removal, primary and secondary leach. It is operated counter-currently such that the solids move from stage to stage counter-currently with the pregnant leach solution. The Copper removal is a series of continuously stirred reactors maintained at 80°C under atmospheric pressure. The primary leach ensures maximum Ni extraction with more than 75 % recovery and minimal dissolution of Cu and Iron. The slurry is injected by means of air pumps into the first compartment of the autoclave via a steam heat exchanger where it is pre-heated to 100°C. The autoclaves are divided into 4 compartments and operated at 135°C and 1000 kPa. It is then conveyed to the secondary leach stage where the extraction of Ni is completed with more than 99 % Ni removal. The slurry is injected via air pumps without preheating into the first compartment of the autoclaves. The autoclaves are divided into 4 compartments and operated at 1000 kPa and at temperatures ranging between 140 and 145°C. The Nickel circuit is comprised of unit operations meant for Lead removal, Cobalt removal, Nickel Electrowinning and Sulphur removal. The lead removal circuit precipitates from the solution into a filter cake by direct injection of Barium oxide. Cobalt is separated from the lead removal discharge stream by using an Outokompu process. This process takes advantage of the differences in stability of oxidised hydroxides of Cobalt and Nickel in the pH ranges of 5.6 – 5.7, recovering Cobalt in the form of $\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$. Nickel is electrowon from the purified Nickel feed solution at 65°C using Lead anodes and Nickel cathodes in a diaphragmed compartment. Starter sheets for the cells are grown on Titanium blanks and Ni is plated on the cathode. The copper circuit is comprised of the selenium removal and copper Electrowinning steps. Selenium is the only impurity that has to be removed from the copper rich filtrate from the secondary leach. Conditions to remove it are provided by a pressure process with Sodium sulphite at a temperature of 80°C. The Copper feed solution is cooled down to

55°C in a plate heat exchanger prior to Electrowinning to prevent excessive mist into the Tankhouse.

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Table 53: Data for the rectifiers at the EW circuits

Parameter	Copper Rectifier	Nickel Rectifier
Number of rectifiers	1.0	3 i.e 2 for 18kA and 1 for 15kA
Voltage(V)	220.0	350.0
Current(A)	15000.0	15000.0
		18000.0
		18000.0
Power(MW)	3.3	11.6
Total Power consumption (MW)	14.9	

There is a total of 3 rectifiers at the EW circuit. Two of them are rated at 18 kA with only one operating at a time and the other one on standby.

Table 54: Data for the cells at the EW circuits

Cells	Copper Cells	Nickel Cells
Number of cells in circuit	116.0	176.0
Residence time(days)	7.0	6.0
Voltage(V)	2.1	4.1
Current(A)	13000.0	15000.0
Power(MW)	3.2	10.8
Total Power (MW)	14.0	
Monthly Power(MWh/cycle)	532.0	1558.7
Total power(MWh/month)	2128.1	7793.3
Total power(MWh/year)	25537.1	93519.4
Annual production(ton/year)	12000.0	21500.0
Electricity consumed per product(MWh/ton)	2.1	4.3

Table 55: Data from the plant's production charts

2009	January	February	March	April	May	June
Current efficiencies at the tankhouse(%)						
Ni	97.4	95.3	96.8	95.8	96.1	97.7
Cu	83.1	83.3	77.7	77.4	80.1	80.1
Energy consumption(MJ/ton Base Metal)						
	26908.0	28113.0	19276.0	N/A	22343.0	24632.0
Coal consumption	9.2	8.6	9.4	9.3	7.3	9.1
Water usage(ML/day)	2.1	1.4	1.9	1.8	1.9	1.8
Product volumes(ton in a single month)						
Ni	1214.3	404.3	1467.4	N/A	1754.9	1544.9
Cu	637.2	184.5	727.5	692.8	679.9	690.9
Co(as CoSO ₄)	38.0	10.5	62.6	63.0	71.5	64.2

Table 56: Comparing the calculated values for overall plant with reported data

Plant (avg)MWh/month	12700.0
Plant Electrical Capacity(avg)	17.6
EW Cells(MWh/month)	9921.4
Fraction of power used by EW cells	0.8

Table 57: Averaged values

Current efficiencies at the tankhouse(%)		
Ni	96.5	
Cu	80.3	
Energy consumption(MJ/ton Base Metal)	(MWh/ton Base Metal)	GWh for the month
	24254.4	6.7
Energy consumption per product metal(Design)	(kWh/ton)	
	Cu	2100.0
	Ni	4300.0

Table 58: Annual energy consumption for EW cells

Annual Energy consumption (MWh)- Capacity	Actual	Design
Cu	32184.8	45150.0
Ni	31069.7	51600.0
Power capacity for Cu	3.7E+00	5.2E+00
Power capacity for Ni	4.5E+00	7.5E+00
	8.2E+00	12.7
Averaged electrical power demand by EW cells(MW)	13	

The annual operation hours for the Copper EW cells is 8640 and 6912 for the Nickel cells

Table 59: Production rates

Product volumes(ton)	Monthly	Actual Annual	Design annual	Production performance
Ni	1277.2	15326.1	21500.0	0.7
Cu	602.1	7225.5	12000.0	0.6

The plant also produces Cobalt in the form of Cobalt Sulphate salt at a monthly rate of 51.6 tonnes.

VIII. Escondida Copper operations

Process description for the concentrators

Ore undergoes size reduction through a primary crusher. It further reduced to size at the milling circuit where it first goes through a SAG mill and a Ball mill. The floatation circuit recovers the desired minerals from milled ore. Water and the milled ore are added to a Floatation Rougher where most of the gangue material is recovered to a Tailings Thickener. The recovered mineral-rich ore is Re-milled and processed through a Floatation Cleaner where concentrate is recovered. A Scavenger Thickener removes any gangue material that was not removed at the Floatation Rougher. Tailings are thickened and excess water is removed and re-used on the plant.

Process description for sulphide ore flowsheet

The low grade sulphide ore is reduced in size and deposited in heaps. Leaching occurs in these heaps by oxidation in the presence of bacteria, air and temperatures favourable for bacterial activity at the **ROM Leach**. The copper enriched solution obtained from the heap leach follows the same **Solvent Extraction** and **Electrowinning** processes same as for the oxide ore.

Process description for oxide flowsheet

The Ore undergoes a size reduction process through a series of **Crushers** and **Screens**. It is later agglomerated with sulphuric acid and deposited in leach heaps. The heaps are irrigated with an acid solution that once enriched is recovered and sent to the solvent extraction plant and then to the electrowinning circuits where copper cathodes are obtained. The cathodes are classified and sent by train to the Port Antofagasta to the various clients.

General information

NB: All the energy consumptions listed on the flowsheets are electrical i.e. Even for the Heap leach, since the energy supplied is for aerating the heap

Table 60: Production information for Escondida Copper(BHP Billiton, 2009)

Infrastructure	Location/Operation
Two open pit mines	Escondida AND Au-Cu-Ag
	Escondida Norte
Two concentrator mines	Laguna Seca
	Los Colorados
Electrowinning plant	Produce cathodes from oxide and sulphide ore
Two pipelines	Transporting concentrate from mine to filter plant

Table 61: Process operations regarding power demands and production (Minera Escondida, 2007)

Energy demand(electrical)	MW	260
Available mineral reserves	tons	1.80E+09
Average copper grade	%	1.59
Expected life time of mine	years	35
Ore processed per annum	ton/annum	370000000
Copper product output	ton/annum	1.50E+06
Output from Low grade ore leaching	ton/annum	180000
Grade range for low-grade	%	0.3-0.7

Table 62: Throughput from concentrators (BHP Billiton, 2004)

Capacity: 1999-Concentrate produced	
Los Colorados(tonnes/day)	120000
Laguna Seca (tonnes/day)	110000
Copper(Tons)	8.27E+05
Gold(ounces)	150000
Silver(Ounces)	3.53E+06

IX. Oxide process flowsheet data

Table 63: Production information for the Oxide flowsheet (Outotec, 2009)

Ore processed ton per annum	2.94E+07
Copper output(ton/annum)	1.50E+05
Head grade (%)	0.75

Table 64: Energy consumption data for the Oxide flowsheet (Outotec, 2009)

Unit/Section	(kJ/lb Cu)	(kWh/kg Cu)		
Primary crusher	640	0.3919	kWh/ton ore	2
Secondary crusher	321	0.1966	kWh/ton ore	1
Tertiary crusher	321	0.1966	kWh/ton ore	1
Heap leaching	640	0.3919	kWh/ton ore	2
Solvent Extraction	1975	1.2095	kWh/kg Cu	1.2125
Electrowinning	3842	2.3528	kWh/kg Cu	2.3589

The plant operates 365 days a year with a 24 hour cycle daily but the Solvent extraction and electrowinning circuits operate at 360 days a year.

Table 65: Electrical power consumption of individual units for the oxide flowsheet

Unit	Capacity(MW) ²⁶	Capacity(MW) ²⁷	Averaged (MW)
Primary crusher	6.71	6.72	6.71
Secondary crusher	3.37	3.36	3.36
Tertiary crusher	3.37	3.36	3.36
Heap leaching	6.71	6.72	6.71
Solvent Extraction	21.00	21.05	21.02
Electrowinning	40.85	40.95	40.90
Total	82.00	82.15	82.08

X. Sulphide leach process flowsheet data

Table 66: Production data for the Sulphide flowsheet

Copper Cathodes	kton/year	180-245
Average Copper output	ton/annum	2.13E+05

Table 67: Rate of energy consumption for the Sulphide flowsheet

Unit/section	kJ/lb Cu	kWh/kg Cu	From Table 1	
ROM leach	720	0.4409	kWh/ton ore	1
Solvent extraction	1975	1.2095	kWh/kg Cu	1.2125
Electrowinning	3842	2.3528	kWh/lb Cu	2.3589

²⁶ Based on the Cu produced annually

²⁷ Based on the ore processed annually

Table 68: Electrical power consumption of individual units for the sulphide flowsheet

Unit/Section	MW (Cu produced)	MW (ore processed)	Average
ROM leach	10.70	9.13	9.91
Solvent extraction	29.75	29.82	29.78
Electrowinning	57.87	58.02	57.94
Total	87.61	87.84	87.73

XI. Concentrators' flowsheet data

NB: Based on the flowsheet for the concentrator route from ore to copper cathodes:

SAG & Ball Milling, Floatation, Smelting

Table 69: Production specifications for the

Head grade (%)	1.5
Copper recovery (%)	77

Table 70: Throughput from each of the concentrators

Throughput	Ton per annum
Laguna Seca	4.64E+05
Los Colorados	5.06E+05

Table 71: Rate of energy consumption for each of the units on the concentrator flowsheets

Unit/Section	kJ/ lb Cu	kWh/ kg Cu		
Primary crusher	275	0.1684	kWh/ton ore	2
SAG mill	1644	1.0068	kWh/ton ore	11.96
Ball Mill	1547	0.9474	kWh/ton ore	11.26
Floatation circuit	622	0.3809	kWh/ton ore	4.53

Table 72: Electrical power consumption of individual units for the oxide flowsheet

Unit/Section	Capacity(MW) ²⁸	Capacity(MW) ²⁹	Average
Primary crusher	18.64	19.17	18.90
SAG mill	111.44	114.62	113.03
Ball Mill	104.86	107.91	106.39
Floatation circuit	42.16	43.41	42.79
Total	277.10	285.10	281.10

Table 73: Overall electrical capacity for each concentrator

Location	Electrical Capacity(MW)
Laguna Seca	134
Los Colorados	147

²⁸ Based on the Cu produced annually

²⁹ Based on the ore processed annually

XII. Appendix C: Quantifying electrical and fuel losses

I. Transmission line losses

The calculated values are comparable with what Eskom is reporting in their annual reports i.e about 10 % of the power transmitted does not reach the destination because of transmission and distribution losses. This sample calculation has been adapted from (Bakshi & Bakshi, 2009)

$$P_{\text{Loss}} = I^2 R + I^2 X$$

A sample calculation for the Skorpion Zinc Refinery is shown below.

Total power demand: 120 MW

Energy required:

Distance of Extra High voltage line at 440 kV: 600 km

Current passing through EHV line: 300 A

Current passing through HV line: 533 A

Distance of High voltage line at 225 kV: 50 km

Resistance of Transmission line: 0.1453 Ω /km

Reactance of the transmission line: 0.2808 Ω /km

$$\text{Power Loss} = 600 \text{ km} * (300 \text{ A})^2 (0.1453 \text{ } \Omega/\text{km} + 0.2808 \text{ } \Omega/\text{km}) + 50 \text{ km} * (533 \text{ A})^2 (0.1453 \text{ } \Omega/\text{km} + 0.2808 \text{ } \Omega/\text{km})$$

$$\text{Power loss} = 29 \text{ MW}$$

This means that when 120 MWh is transmitted over the transmission and distributed, 29 MWh is lost.

This value is calculated at each hour when power is supplied to the refinery. To evaluate the annual electrical losses, the number calculated above was evaluate at each hour over the whole year and then added together. The same method was used when a solar

power plant is co-located at the refinery to evaluate how the electrical line losses would be affected by the co-location.

The following tables, shows the parameters used to calculate the transmission and distribution line losses for all the other operations.

Table 74: Estimated lengths of the transmission lines used to evaluate transmission losses for each operation

Operation	Length of EHV line (km)	Length of HV line(km)
Skorpion Zinc	600	50
Manganese Mine Company	0	80
Rustenburg Base Metals Refiners	100	80
Laguna Seca	200	75
Los Colorados	200	69
Sulphide flowsheet	200	74
Oxide flowsheet	200	65

XIII. Quantifying conversion losses

The AC-DC conversion losses have been calculated using the assumption that when power is converted from AC-DC and vice versa, 9 % of the power passed through the Rectifier in the case of AC-DC conversion or Inverter in the case of DC-AC conversion is lost through the conversion process.

XIV. Quantifying fuel losses for Etango Uranium operation

The Diesel generators where estimated to have a fuel-to-electricity efficiency of 75 %. The fuel lost when transporting the fuel from Walvis Bay to the site which covers a distance of about 30 km was estimated using the capacity of the Diesel tankers and the fuel consumption of the diesel generators. The total fuel losses covered transportation and inefficiency of the diesel generators. The following shows a sample calculation of how these losses were evaluated.

The fuel consumption of the generators was based on the assumption that:

1 litre of diesel produces 3.71 kWh worth of energy.

This diesel consumption was calculated every hour and summed up to obtain diesel consumption on a daily basis. The daily consumption was used to evaluate the re-fuelling rate required for the trucks to deliver diesel onsite. An assumption that there is storage onsite with enough fuel to supply power for a day was used.

Table 75: Data used to evaluate fuel losses at Etango Uranium Refinery

Fuel generator consumption (liters)	70838285
Daily fuel consumption (liters)	194077
Hourly consumption (liters)	8087
Daily refueling rate	9
Onsite storage required (surplus enough for an extra day) (liters)	388155
Number of trips required	18
Fuel efficiency of trucks (km/litre of diesel)	0.35
Single trip distance travelled (km)	60
Fuel consumption from transportation per day	388
Annual fuel consumption (Transport)	141677

XV. Appendix D: Performance of the co-located solar power plants

The section presents the performance of the solar power plants co-located to each of the refineries.

II. ETANGO URANIUM



Figure 47: Aerial view of the Etango Uranium site (Generated using Google Earth, 2010)

A solar power plant for this operation would meet the refinery's energy demands when the sun is available and charge the batteries when surplus energy is generated. This will be used in conjunction with the diesel generators that are currently used on the plant.

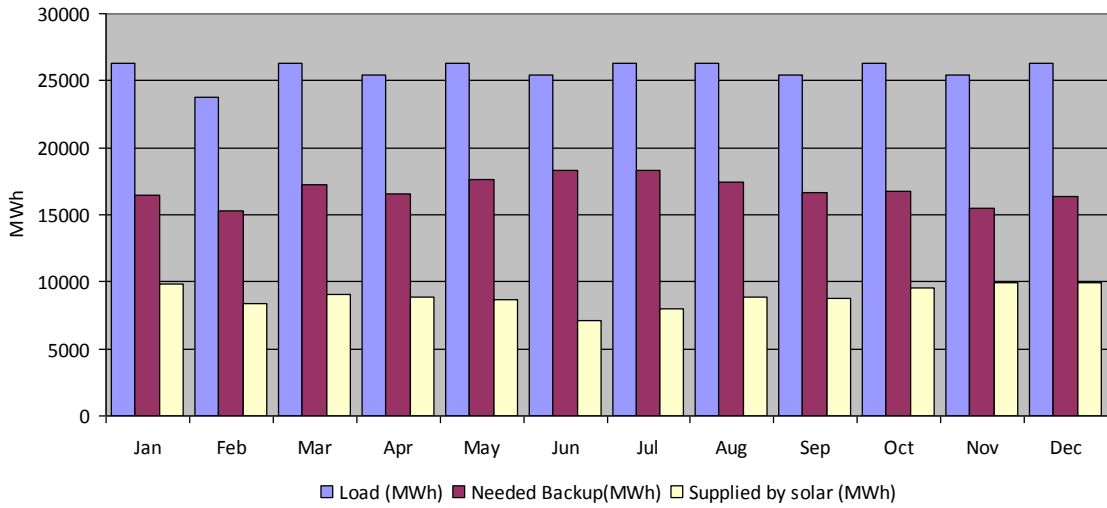


Figure 48: Monthly load, backup and excess electricity for Etango Uranium

The plant has an annual energy capacity of 263 GWh. The figure above shows the monthly load, backup required and the excess energy that can be generated if solar energy was deployed for this refinery.

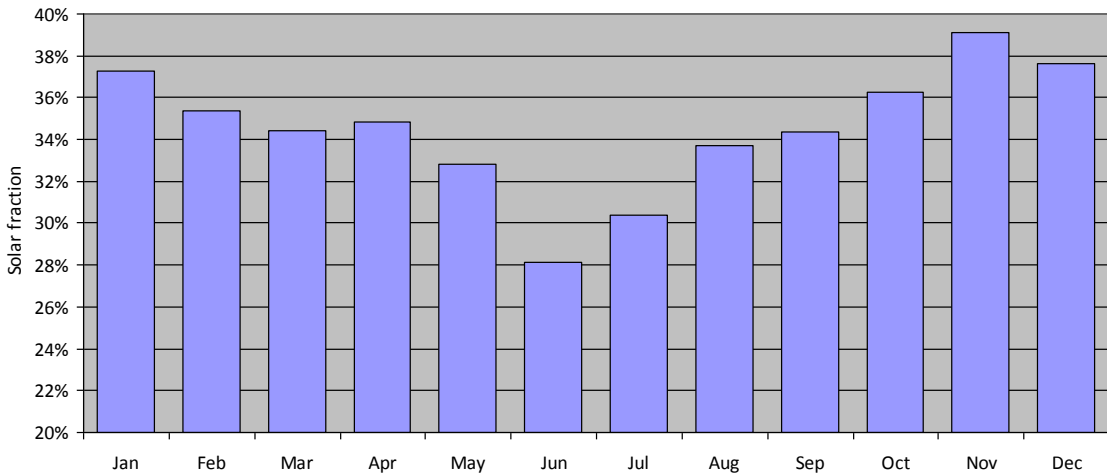


Figure 49: Monthly solar fraction for Etango Uranium

The figure above, shows the fraction of the load that can be potentially supplied by solar energy.

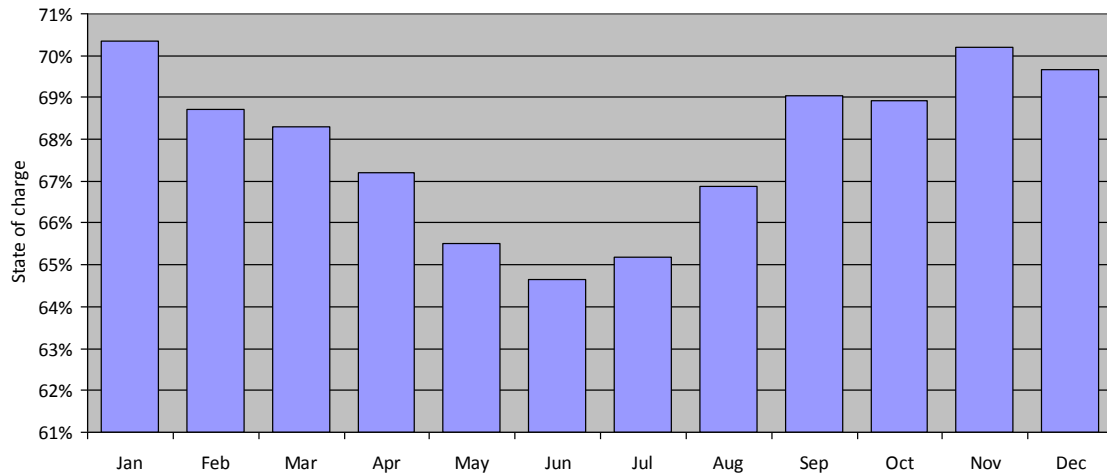


Figure 50: Monthly state of charge for the batteries for Etango Uranium

For this operation, batteries will be used to store the surplus energy generated from the sun. The figure above shows the monthly state of charge for these batteries.

Resulting energy and fossil fuel savings

The annual fuel savings that would result from the use of solar energy is shown on the table below. The use of solar energy would potentially cut fuel consumption by up to 51 % for that Etango mine. This does not account for the fuel used during transportation of fuel from the depot to the mine.

XVI. SKORPION ZINC REFINERY



Figure 51: Aerial view of the Skorpion Zinc Refinery (Generated using Google Earth, 2010)

Skorpion Zinc AC solar power plant

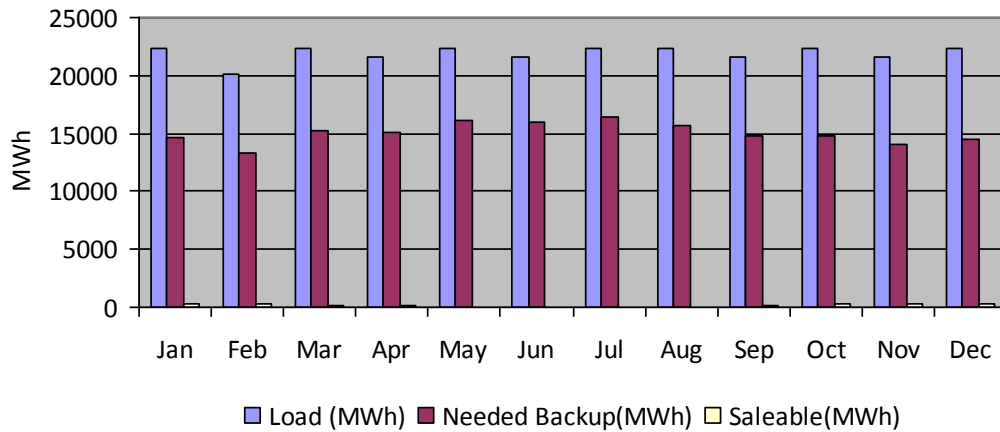


Figure 52: Monthly Load, Needed backup and saleable electricity from a solar power plant for AC load at Skorpion Zinc refinery

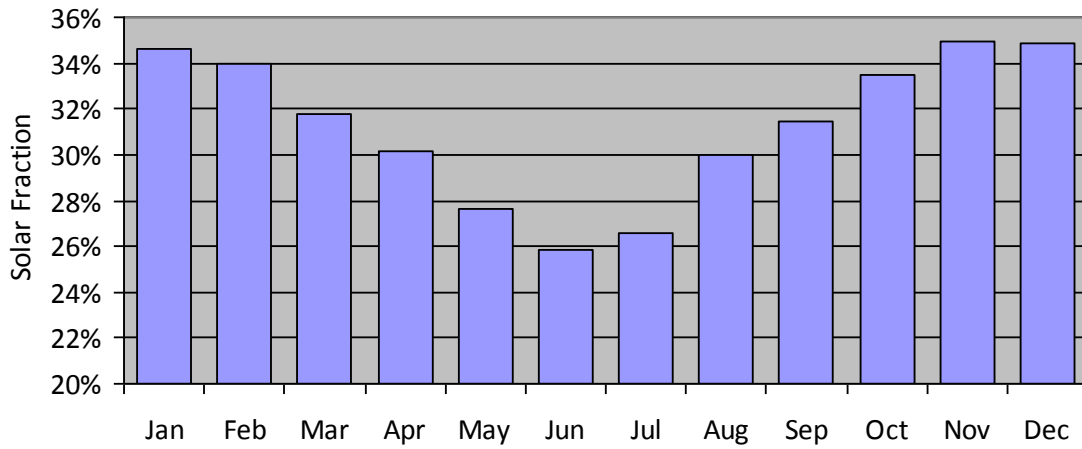


Figure 53: Solar fraction for AC load at Skorpion Zinc refinery

Skorpion Zinc DC solar power plant

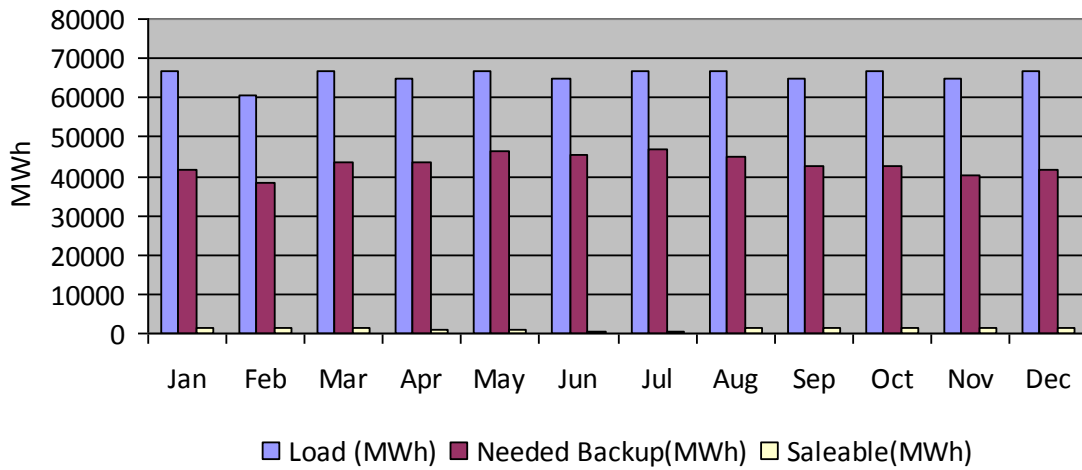


Figure 54: Monthly Load, Needed backup and saleable electricity from a solar power plant for DC load at Skorpion Zinc refinery

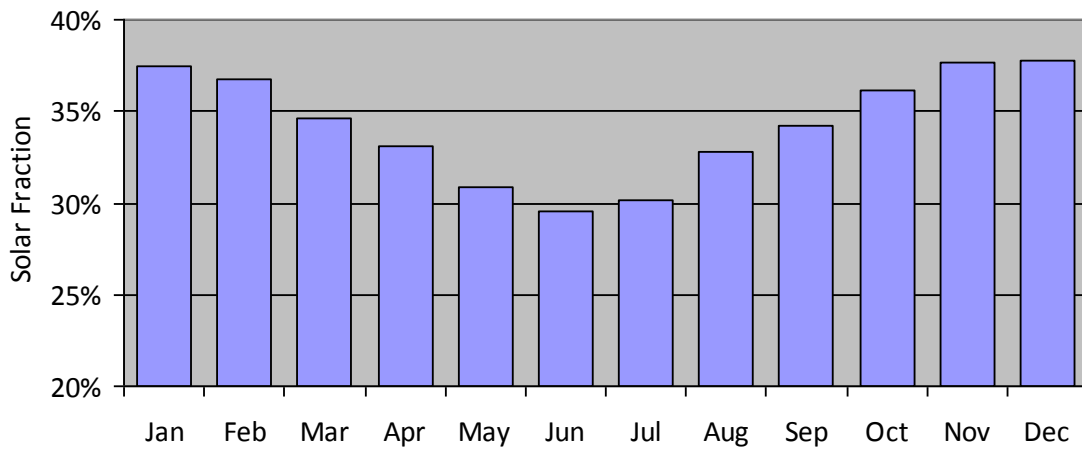


Figure 55: Solar fraction for DC load at Skorpion Zinc refinery

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XVII. RUSTENBURG'S BASE METALS REFINERY



Figure 56: Aerial view of the RBMR operation (Generated using Google Earth, 2010)

BMR AC solar power plant

The AC power plants will require inverters which convert DC power to AC power to supply the relevant energy product to different parts of the plant.

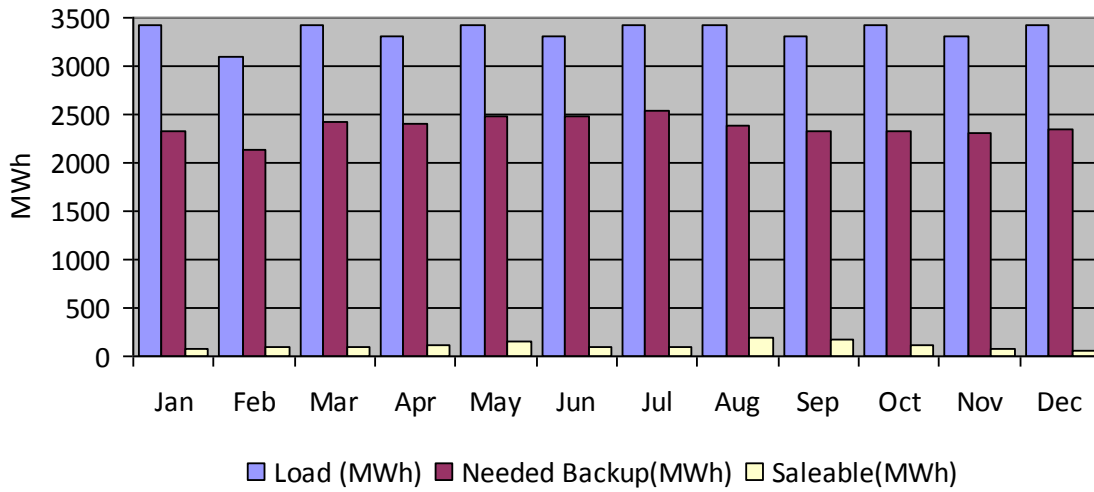


Figure 57 : Monthly Load, Needed backup and saleable electricity from a solar power plant for AC load of BMR

The figure above shows the monthly performance of a solar power plant which supplies AC electrical power to the refinery.

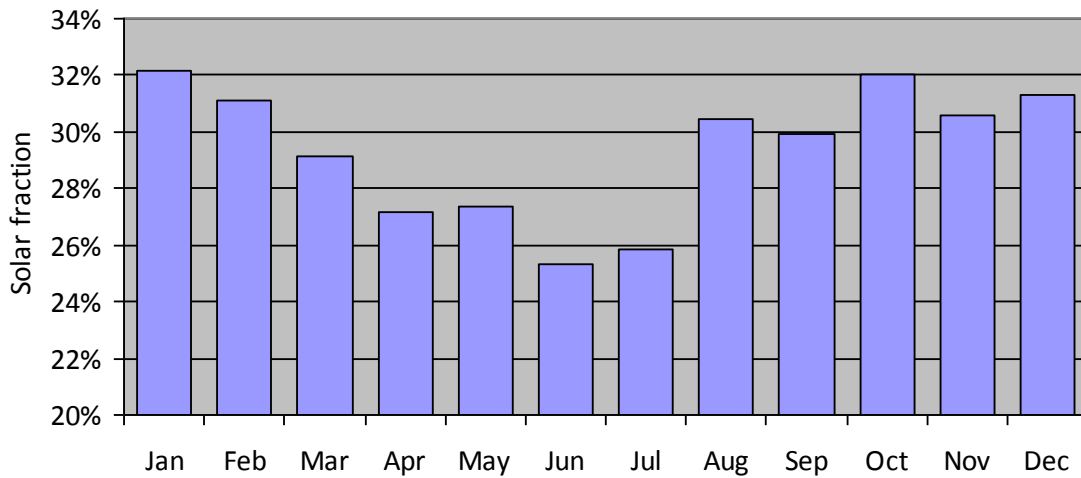


Figure 58 : Solar Fraction for AC load of BMR

The figure above shows the fraction of the load that can be supplied by solar energy on a monthly basis. This is accounted for on a 24 hour basis including the times when the sun is not available.

BMR DC solar power plant

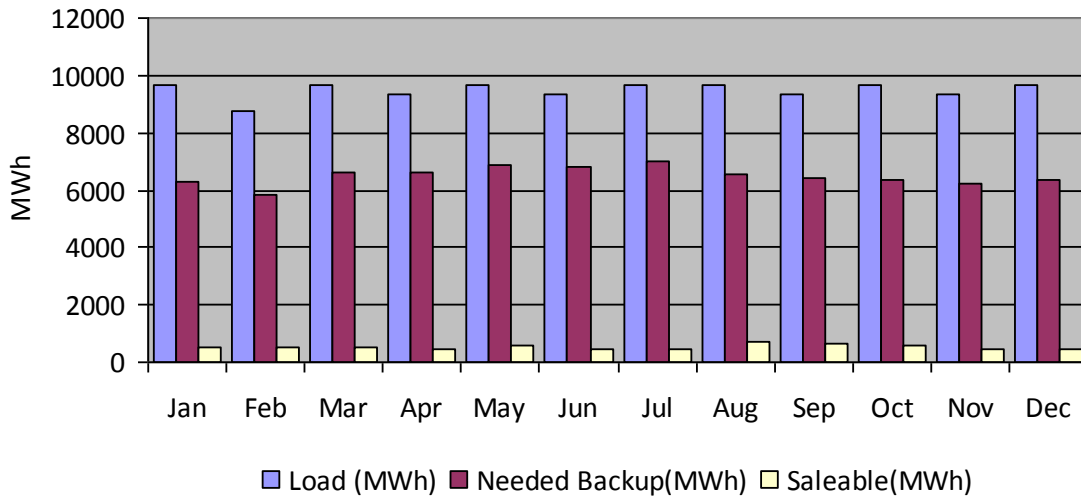


Figure 59 : Monthly Load, Needed backup and saleable electricity from a solar power plant for DC load of BMR

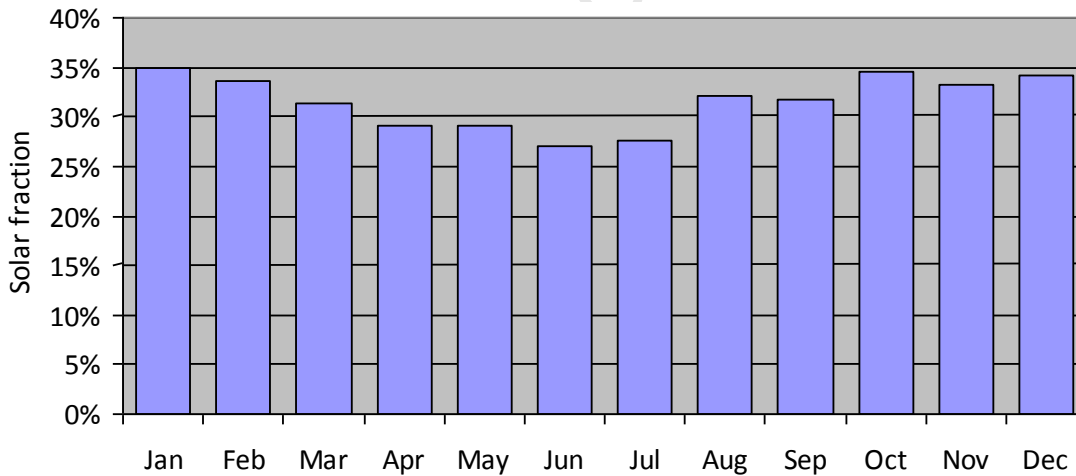


Figure 60 : Monthly solar fraction for DC load of BMR

It can be noted that when comparing the performance of an AC and DC power plants, the DC shows a better performance. This is attributed to the fact that there are no electrical losses for the DC, since there is no need to convert power from DC to AC. From this it can be concluded that a DC configuration is better than using solar energy to supply power for AC electrical power.

XVIII. ESCONDIDA COPPER



Figure 61: Aerial view of the Escondida mines (Generated using Google Earth, 2010)

Laguna Seca

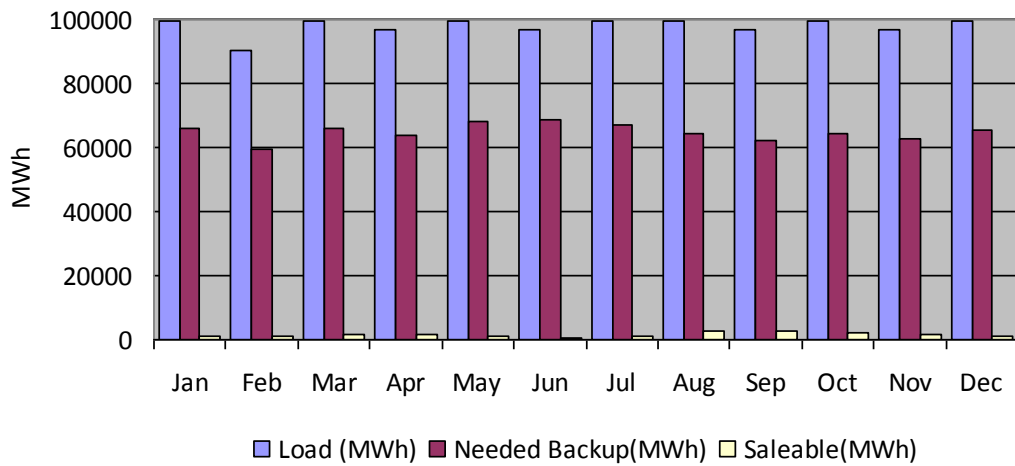


Figure 62 : Load, needed backup and saleable energy for Laguna Seca concentrator

Los Colorados

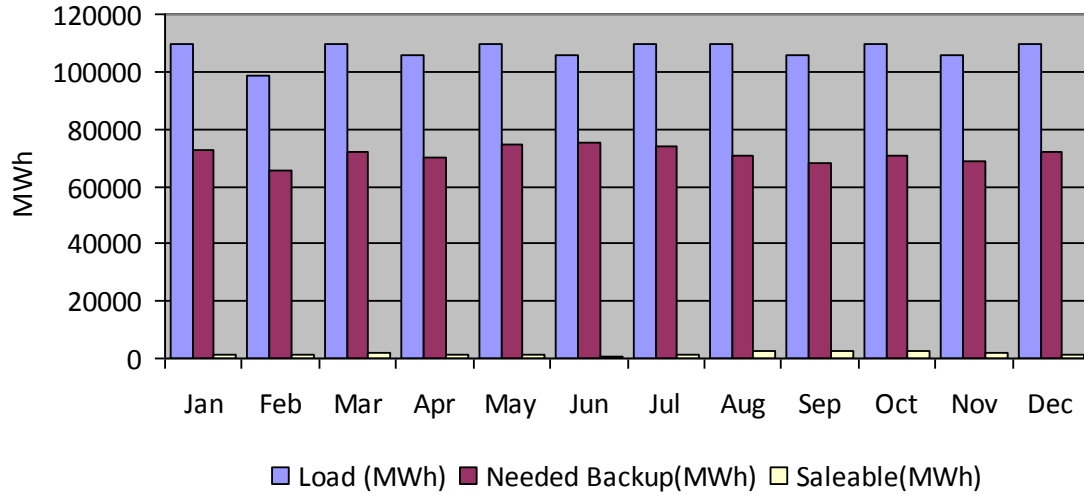


Figure 63 : Load, needed backup and saleable energy for Los Colorados concentrator

Sulphide ore AC solar power plant

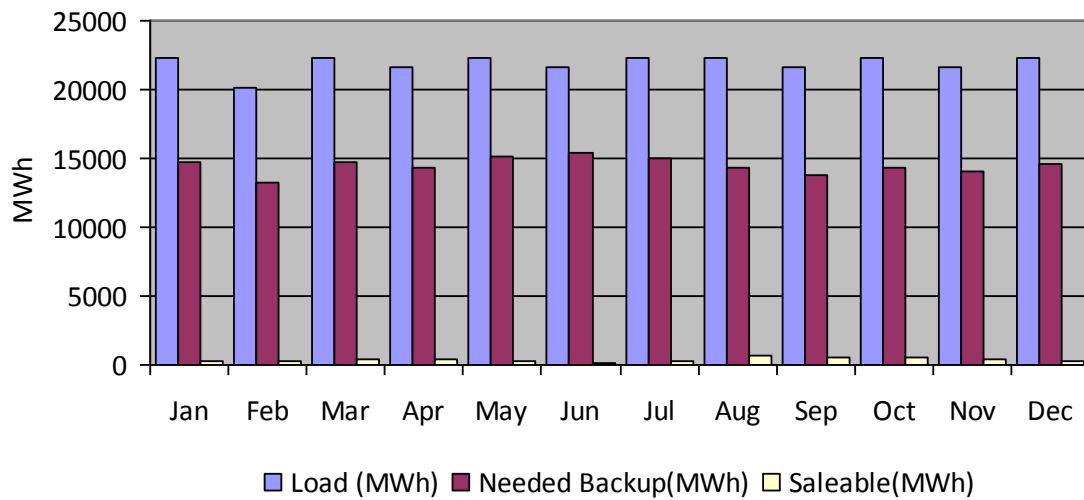


Figure 64 : Load, needed backup and saleable energy for Sulphide ore AC load

Sulphide ore DC

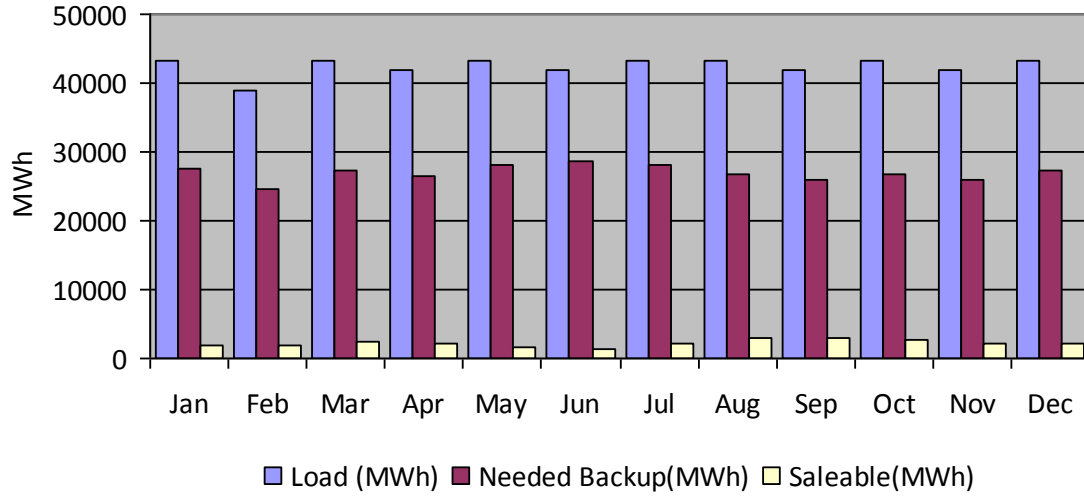


Figure 65 : Load, needed backup and saleable energy for Sulphide ore DC load

Oxide ore AC

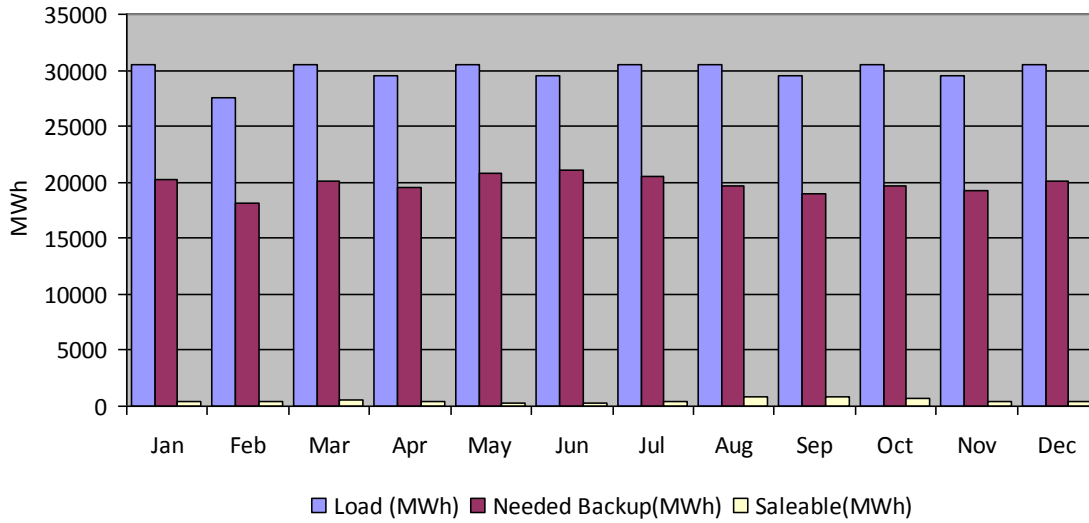


Figure 66 : Load, needed backup and saleable energy for Oxide ore AC load

Oxide ore DC

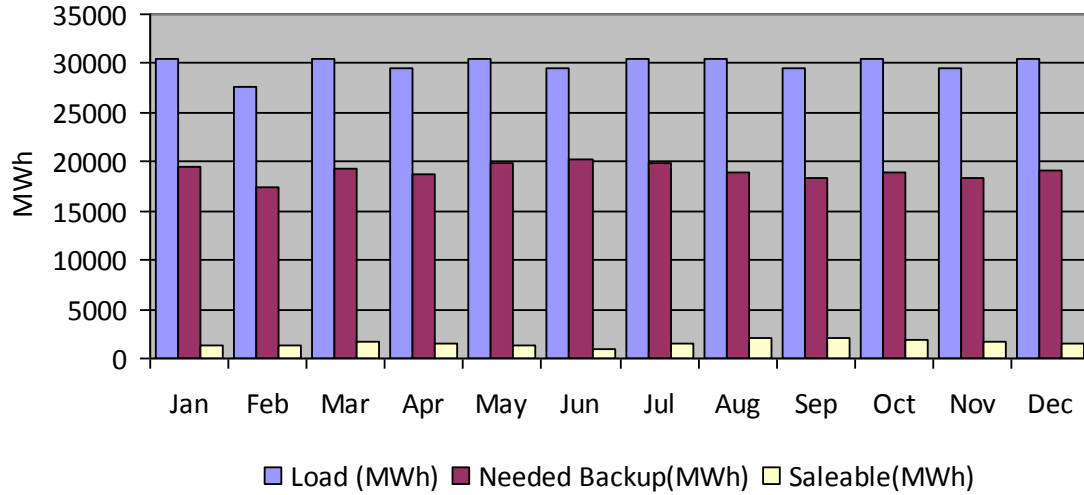


Figure 67 : Load, needed backup and saleable energy for Oxide ore DC load

Solar fraction for Escondida operations

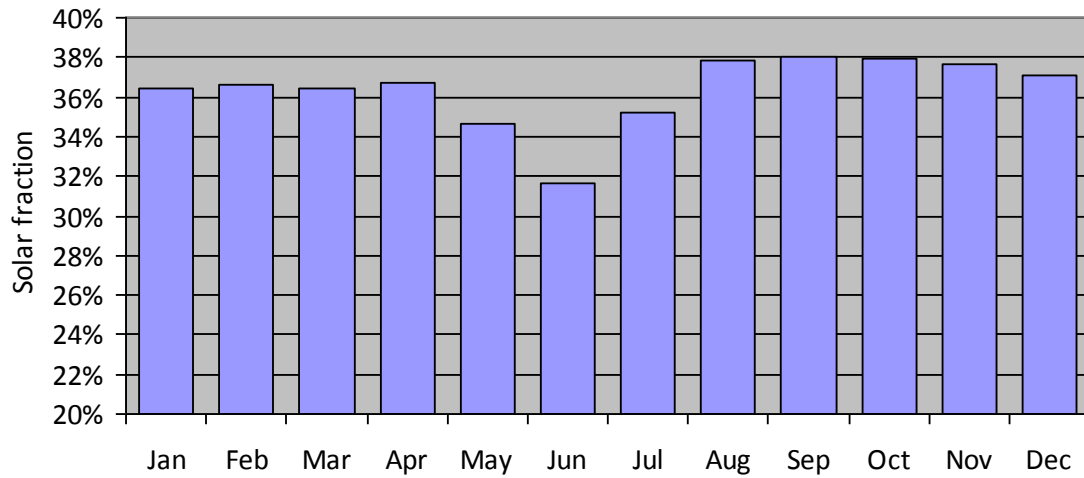


Figure 68 : Solar fraction for all DC loads at Escondida

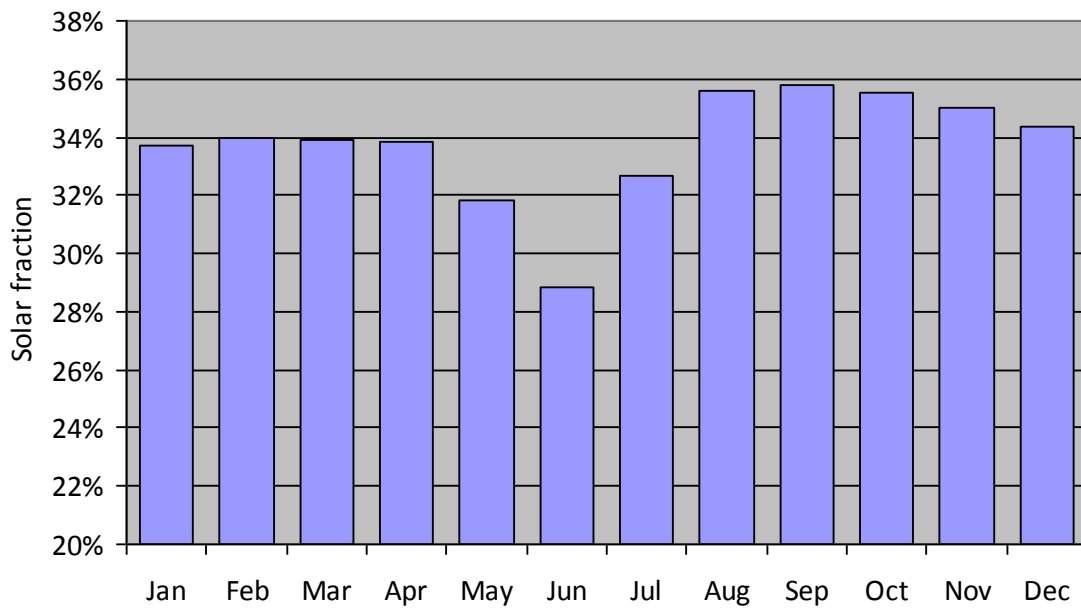


Figure 69 : Solar fraction all AC loads at Escondida

XIX. MANGANESE METAL COMPANY

University of Cape



Figure 70: Aerial view of the Manganese Metal Company (Generated using Google Earth, 2010)

MMC AC solar power plant

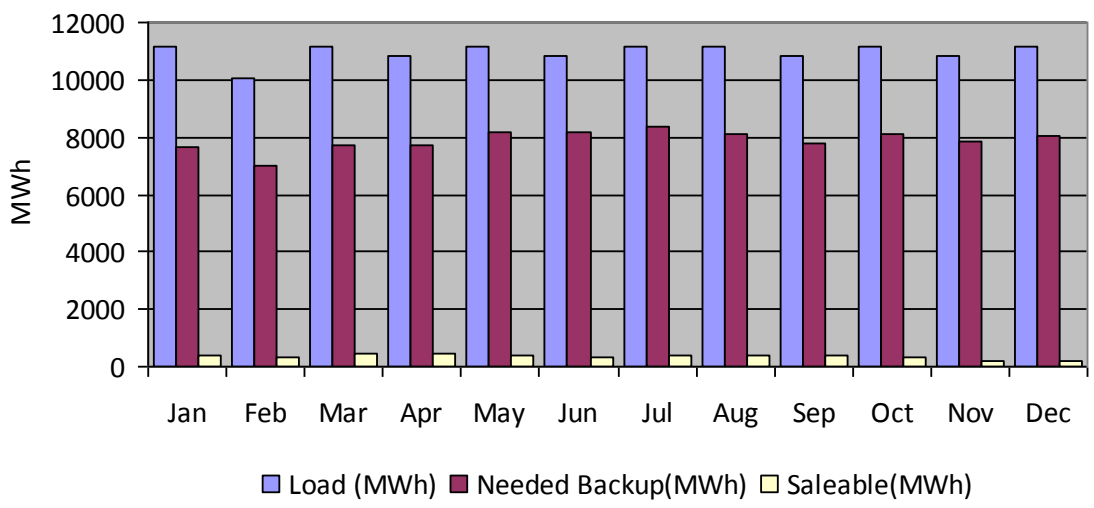


Figure 71: Monthly Load, Needed backup and saleable electricity from a solar power plant for AC load at MMC

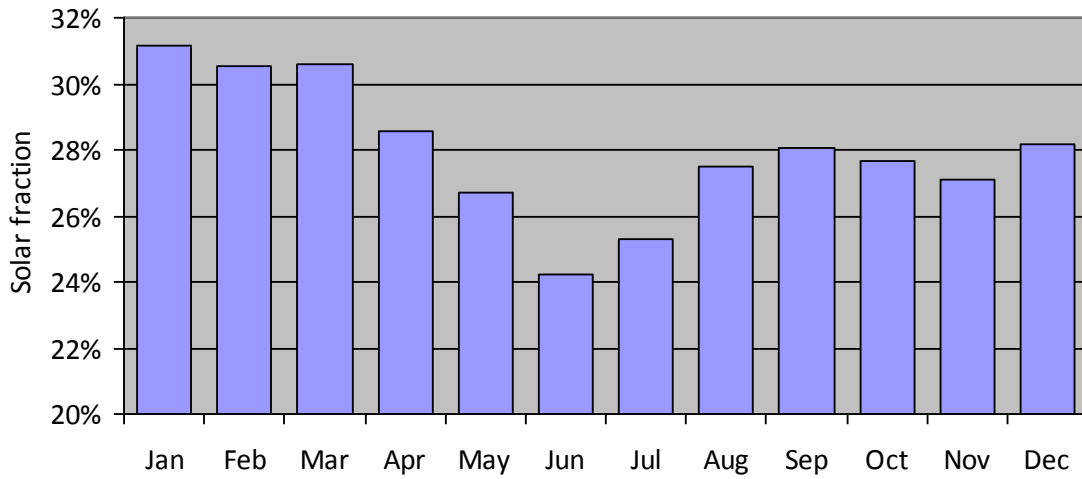


Figure 72: Solar Fraction for AC load at MMC

MMC DC solar power plant

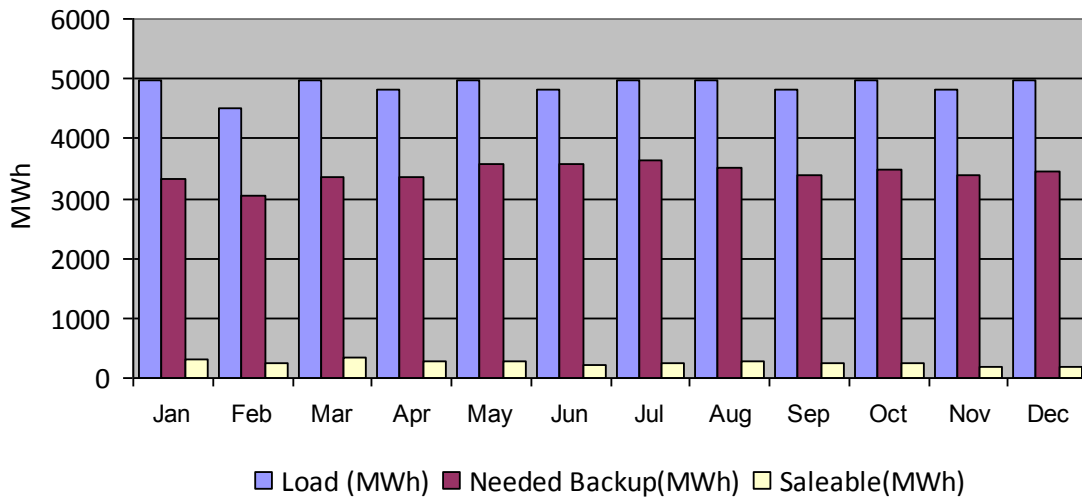


Figure 73: Monthly Load, Needed backup and saleable electricity from a solar power plant fro DC load at MMC

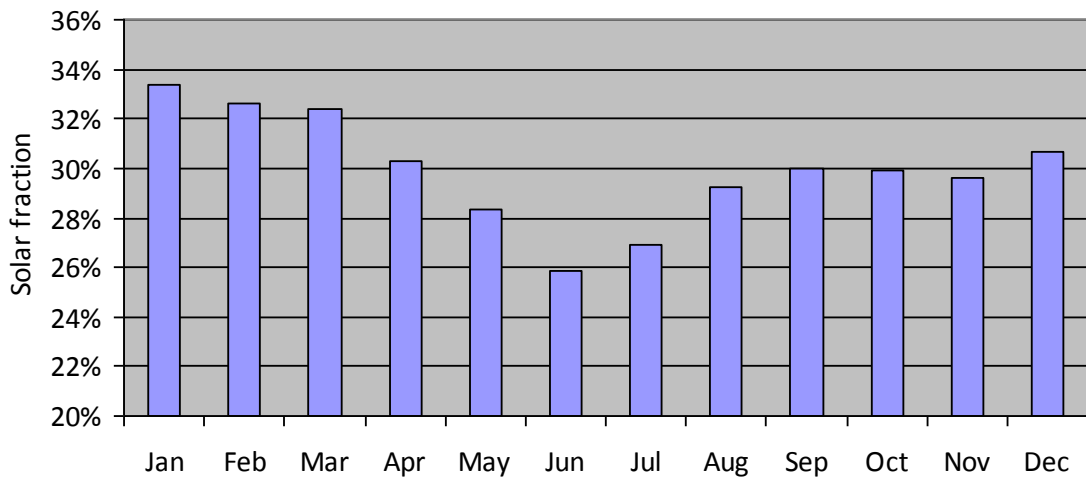


Figure 74: Solar fraction for DC load at MMC

University of Cape Town