The conceptual design of an integrated energy efficient ore reduction plant

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ABSTRACT

Title: The conceptual design of an integrated energy efficient ore reduction plant.

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Keywords: Energy efficiency, pyrometallurgical ore reduction plant, energy conservation, energy efficiency, heat recovery

This study explores ways to determine the energy efficiency of a pyrometallurgical ore reduction plant and measures to improve it. The feasibility of building a commercial plant - that is more energy efficient, has a low energy cost, and can operate independently and cost-effectively of external electricity supply - is determined. The need for energy efficiency is expanded to three questions: how should the energy efficiency of the plant be determined, what is the efficiency of the existing plant and to what level it can be improved.

Literature and other relevant sources were consulted. Twenty potential energy conservation measures were identified through a literature study. A multi-criteria decision-making approach resulted in the selection of ten measures for conceptual implementation. The measures ranged from high-efficiency motors, solar power, heat recovery with thermal oil and various heat engines, to pressure recovery with turbo-generators.

A case study approach was followed with the energy efficiency of an existing prototype plant the subject being studied. The energy usage of the existing plant and feasible measures to improve the performance were empirically observed. The impact of these measures was modelled and the results of the conceptual implementation determined. Two measures that were implemented during the study are also described and the results reported.

The study found that the energy efficiency of the plant could be determined by the ratio of product exergy to input energy. By incorporating a number of energy conservation measures conceptually the internal efficiency of the prototype plant was conceptually improved from the current 17% to 22% and as a result externally supplied electricity reduced by 47%. The results were extrapolated to a future commercial plant and energy efficiencies of 26% on-grid and 21% off-grid predicted.

This study suggests that a significant improvement in energy efficiency and energy cost can be achieved by integrating appropriate energy conservation measures into the existing and future plants.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

BC	Brayton Cycle
Bn	Billion (10^9)
CAPEX	Capital Expenditure
CFPP	Coal-Fired Power Plant
DOL	Direct On Line
ECM	Energy Conservation Measure
EFGT	Externally Fired Gas Turbine
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EROI	Energy Returned on Investment
FCP	First Commercial Plant
G2GEE	Gate to Gate Energy Efficiency
IAC	Inlet Air-Cooling
IE	International Electrotechnical Commission
IFGT	Internally Fired Gas Turbine
ISO	International Standards Organisation
KRC	Kalina Rankine Cycle
LHV	Lower Heating Value
LP1	Letaba Plant 1
LP2	Letaba Plant 2
LTIFR	Lost-Time Injury Frequency Rate
OPEX	Operating Expenditure
ORC	Organic Rankine Cycle
PV	Photovoltaic
RC	Rankine Cycle
S2GEE	Source to Gate Energy Efficiency
SAF	Submerged Arc Furnace
SC	Stirling Cycle
SCRC	Super-Critical Rankine Cycle
SRC	Steam-Based Rankine Cycle
STIG	Steam Injected Gas Turbine
TEG	Thermoelectric Generator
TLC	Trilateral Cycle
US	United States
USA, US	United States of America
VPSA	Vacuum and/or Pressure Swing Absorption
VSD	Variable Speed Drive
VVID	Variable Vane Inlet Damper
WI	Water Injection

NOMENCLATURE

°C	Celsius
c	Cent
c/MJ	Cent per megajoule
cP	Centipoise
c_p	Constant pressure specific heat
E	Energy
E_x	Exergy
g	Gram
g/s	Gram per second
GJ	Gigajoule
GJ/t	Gigajoule per ton
h	Enthalpy
K	Kelvin
km	kilometer
kg	Kilogram
kJ	Kilojoule
kJ/kg	Kilojoule per kilogram
kJ/s	Kilojoule per second
kl	Kilolitre
kPa	Kilopascal
kV	Kilo-volt
kW	Kilowatt
kWh	Kilowatt-hour
kWh/t	Kilowatt-hour per ton
m	Meter
$\dot{m}$	Mass flow
m^2	Square meter
mA	Milli-Ampere
MJ	Megajoule
MJ/s	Megajoule per second
MJ/t	Megajoule per ton
MPa	Megapascal
MW	Megawatt
MWh	Megawatt-hour
MWh/t	Megawatt-hour per ton
Nm^3	Normal cubic metre
Pa	Pascal
P	Pressure
Q	Heat or thermal energy
R	Rand
s	Second
S	Entropy
T	Temperature
T_0	Environmental temperature
TWh	Terawatt-hour
W	Watt
U	Internal energy, in Joule, kJ, MJ, GJ
ρ	Density, in kg/m^3
γ	Specific heat ratio, dimensionless
ΔT	Temperature difference, in Kelvin
η	Efficiency, dimensionless

Note: All pressure values in this study are gauge values unless otherwise indicated.

LIST OF COMPOUNDS

C	Carbon
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_3	Carbonate
Fe	Iron
FeMn	Ferromanganese
Fe_3O_4	Ferric oxide
H_2	Hydrogen
HC FeMn	High carbon ferromanganese
Mn	Manganese
MnO	Manganese oxide
MnO_2	Manganese dioxide
SiO_2	Silica dioxide

CHAPTER 1

Chapter 1 defines the problem addressed by this study. Potential solutions are identified through a literature survey. The methodology that is followed in this study is described.

Travel is fatal to prejudice, bigotry, and narrow-mindedness, and many of our people need it sorely on these accounts. Broad, wholesome, charitable views of men and things cannot be acquired by vegetating in one little corner of the earth all one's lifetime. ~Mark Twain

1 Introduction

1.1 Background

From prehistoric times man required metals for different purposes. Even epochs in history are named according to the dominant metal of the time, for example the Bronze Age and the Iron Age. Today metals are used in numerous applications – from structural steel used in the construction of buildings, bridges and dam walls; safety pins and paper clips; to the metals used in cars, ships and trains.

The primary sources of most metals are oxides in the earth’s crust. After mining and some form of beneficiation, the oxides are reduced to metal using ore reduction plants. The reduction process moves the oxygen molecules from the metal oxide to a reductant such as carbon, resulting in metal (the product) and an oxidised reductant such as carbon dioxide, or CO_2, (the waste). Pyrometallurgical reduction processes occur at high temperatures; in the case of manganese (Mn) ore the temperature must be above 1 250°C for the reduction of manganese oxides to manganese to occur [1].

Pyrometallurgical ore reduction plants (or smelters) require ore containing metal oxides, coal, electricity and water (and oxygen in the case of the AlloyStream^{TM} process) to function. The placement of smelters is therefore significantly affected by the availability of these resources.

Smelters are intensive energy converters with most of the energy converted by the furnace, the primary high-temperature device in the plant. There are many types of furnaces in industries other than the ore reduction industry - such as glass making, cement manufacturing and power generation. Some solutions to the challenges addressed in this study were obtained from these “non-ore reducing” industries.

This study is based on AlloyStream’s Letaba plant. Letaba was built during the period 2010 to 2011. It started operating in February 2012. It is intended as a pre-commercial technology demonstrator (or prototype) of the AlloyStream^{TM} process, and also as a test bed for technology development and knowledge growth. Although unique in some aspects it uses the same energy sources as other pyrometallurgical plants.

Electrical and chemical energy that enter the plant is converted into heat and work, most of the energy conversion occurs in the furnace vessel. Here “work” means the increase in potential energy of the ferromanganese (FeMn) product above the manganese ore. The difference between the energy entering the plant and the work performed appears as waste heat that is rejected to the environment. Efficient use of energy is an economic requirement. In this study a conceptual redesign of the as-built plant is performed in order to improve the work-to-input energy ratio, or energy efficiency.

The configuration of Letaba as it entered service for the first time is called Letaba Plant 1 (LP1). The proposed energy efficient Letaba configuration is called Letaba Plant 2 (LP2). The first commercial plant is abbreviated to FCP in this document.

1.2 The need

AlloyStream is developing a new technology for the production of ferromanganese and other metals from low-grade ores. Their prototype smelter entered operation in February 2012. This study was initiated as part of the ongoing technology development program of the organization.

LP1 presents a unique opportunity to use as a case study and test bed for energy efficiency improvement in a smelter. Energy cost is currently between 20% and 25% of the LP1 cost base and is expected to increase at a rate higher than inflation. A significant reduction in energy cost is a key for the technology to achieve economic viability.

Energy efficiency is, however, only one of the requirements for a commercially successful smelter. Typical high-level requirements are:

- Low safety risk
- High energy efficiency
- Low capital expenditure (capex) and operating expenditure (opex)
- Quick deployment time
- High yield

Safety risk

High-temperature processes have inherent safety risks. In smelters liquid materials at high temperature can quickly destroy containing vessels, and it can cause explosions when it comes into contact with water or other substances with low boiling points. In the past, explosions have been experienced in many smelters, often because water and liquid metal (or slag) came into contact with each other in an uncontrolled way [2]. The mechanism of this type of explosion is probably a boiling-liquid-expanding-vapour explosion [2, 3]. This mechanism is believed to be the cause of explosions in furnaces at Empangeni and Cato Ridge [4]. In the drive to reduce the energy consumption per ton of metal produced and to increase the refractory life, furnace designs tend to rely heavily on water-cooling, thereby increasing the risk of explosions.

Energy efficiency

The energy used by smelters:

- Powers the reduction process.
- Maintains the high internal temperature of the furnace vessel.
- Drives the support processes, such as the water-cooling system, off gas handling, lighting and others.

Most of the energy that enters the smelter exits the plant as low-level waste heat. Only a fraction of the input energy is converted into process energy or work. In this document the energy efficiency of the plant is expressed as the ratio of the theoretical process energy to the total average energy entering the plant. Another measure used in industry is the electrical energy required by the furnace to produce one ton of metal – expressed in kWh/ton.

The energy efficiency obviously impacts on the profitability of the smelter, but it is also important from a placement, rapid deployment and an environmental point of view. Ore bodies are often found in underdeveloped parts of the world where electrical grid power is insufficient, or does not exist at all. Improved electrical energy efficiency moves the plant closer to a possible self-generation configuration. Reduced energy use is also advantageous from an environmental impact point of view (fewer CO_2 emissions for example) and operating cost.

Capex and opex

Capex and opex are driven by a number of factors. Placement affects start-up time, construction cost, inbound and outbound logistic cost. The design determines to a great extent what the plant will cost to build, how well the plant will perform over its lifecycle, and how dependent it will be on external resources (such as electricity supply via a grid as well as bulk water supply). There is a trade-off between capex and opex – in the case of Letaba, capex had to be minimised even though it was known that it would inflate the opex. In the case of a commercial plant the focus will be more on opex reduction, thus resulting in higher capex.

Financial methods such as net present value, return on investment, and payback period are used to determine the optimum trade-off between capex and opex. These methods also reduce the risk attached to the investment decision. In this study the simple payback period method will be used to evaluate the financial value of the various measures aimed at improving the plants' energy efficiency.

Typical capex of a ferromanganese smelter is R20 000/ton per year, for example: a smelter that can produce 10 000 ton per year will cost in the order of R200 000 000 [5]. Opex must be below R12 000/ton to achieve an operating profit at the 2013 London Metal Exchange price for high carbon ferromanganese (HC FeMn).

Deployment time

Deployment time is the time taken from the moment that funds for the building of the plant are approved to the actual plant start-up. The deployment time is primarily affected by the following factors:

- Governmental approval to operate – this usually requires a successful environmental impact assessment process, including an air emission license. The government approval for Letaba took two years.
- Construction of external infrastructure, such as electricity and water supply systems, and roads and rail facilities if non-existent (up to five years).
- Manufacturing of specialised equipment (up to two years).
- Construction of the facilities and erection of the plant (up to two years).
- Commissioning (three to six months).

Ore deposits are often located in underdeveloped parts of the world where bulk water and electrical power are not available. Smelters also compete with local communities for resources. This can result in a negative outcome for the licensing application, or very tight requirements set by the authorities for the use of scarce resources. An example of the potential impact of such delays is the substantial write-down Anglo American had to perform on its Minas-Rio investment [6].

A smelter that generates its own electricity and uses water sparingly can significantly reduce deployment time resulting in cost savings.

Yield

The yield is defined as the ratio of mass of metal leaving the plant as product to the mass of metal entering the plant in the ore. The yield is primarily determined by the metallurgical process technology. The process parameters required for optimum yield are viewed throughout this study as a constraint to be met by the conceptual design.

1.3 Literature survey

Before the literature survey was started the need was already known: to identify ways of improving the energy efficiency of LP1. With the survey answers to the following questions were sought:

1. What are typical (benchmark) levels of energy efficiency in smelters?
2. Which methods or technologies are available to improve the energy efficiency?
3. What are the capability and maturity of the available technologies?

The literature survey explored three main groupings: books, academic journals and non-academic sources.

1.3.1 Benchmark process energy required in HC FeMn-producing smelters

Tangstad and Olsen calculated the process enthalpy (defined as the energy required at constant pressure to produce HC FeMn from ore) as between 1 495 kWh/ton and 2 174 kWh/ton, depending on the ore composition and water content [1]. Process enthalpy is defined as the change in enthalpy from reactants to products during the reduction reactions. Their calculations are based on a submerged arc furnace (SAF) with a top-of-charge temperature of 200°C to 250°C. This is the temperature at which the off-gas (by-product of the process) exits the furnace. Tangstad and Olsen followed a fundamental approach. The higher value is based on an ore water content of 10% and a non-optimum ore composition. The calculation is based on standard states for both reactants and products. Their sub-optimum mix contains 339 kg carbon per ton of metal produced.

BHP Billiton uses 2 600 kWh as the electrical energy required to produce one ton of HC FeMn in an SAF [7]. Assore uses a value of 2 650 kWh/t for an open SAF. None of these values include the carbon (or coal) enthalpy. The carbon-to-metal ratio can be as high as 0.9 to 1 [8].

The process enthalpy for the Letaba furnace is calculated as 2 951 kWh/t [9]. The enthalpy of the products is at the furnace internal temperature of 1 550°C.

Wall calculated the exergy efficiency (exergy is work, or the ability to do work) of Swedish iron production [10]. He found the exergy of the ore after mining to be 0.51 MJ/kg and the iron after reduction to be 6.91 MJ/kg. The average input energy for mining of the ore and reduction to iron was 32.9 MJ/kg, giving an exergy efficiency of 21% for the industry.

1.3.2 Literature primarily addressing plant-wide energy saving techniques

Soma and Chiogioji list two questions in Chapter 2 of the Handbook of Energy Systems Engineering that need to be answered to identify areas for energy savings [11]:

1. Which areas have significant potential for savings?
2. Which specific measures should be used to achieve savings?

An example of a site energy and utility diagram with energy balances is given by Soma and Chiogioji. They stress the importance of energy audits, energy balances and energy monitoring and accounting. They describe four energy accounting techniques. The activity method will be used in this study. The term “energy conservation opportunities” is used and suggestions as to how energy conservation opportunities can be evaluated are given. In this study the payback period method will be used to evaluate the financial value of the various measures.

Soma and Chiogioji also list a number of general measures to consider. These are housekeeping (or proper operations), equipment and process modifications, and integrated operations. Specific measures mentioned are utilisation of waste heat, improved efficiency motors, variable speed drives (VSDs) and lighting efficiency improvements. Effective heat utilisation is also covered by Fazolare and Smith in Chapter 2 of the Handbook of Energy Systems Engineering [11]. They emphasise management of energy flow and waste heat recovery and list a number of such measures. Of the heat recovery measures the Steam-based Rankine Cycle (SRC), externally heated gas turbine and Stirling Cycle (SC) were considered in this study.

Doty and Turner use the term “energy conservation measure” or ECM [12]. They cover a broad range of ECM topics. A similar range of topics is covered by Thumann and Mehta [13]. Topics of relevance to this study are:

- Effective energy management and energy auditing - mass and energy balance is one of the analytical techniques used in this study.
- Fired system efficiency analysis, preheating of combustion air, heat recovery, pulse combustion, optimised air-fuel ratios and VSDs.
- Cogeneration.
- Waste heat recovery (heat-to-heat and heat-to-electricity).
- High-efficiency motors and matching motor size to load.
- Energy management control systems.
- Lighting efficiency measures.

- Energy systems maintenance.
- Use of alternative energy such as photovoltaic (PV) solar.
- Commissioning, measurement and verification.

Chan et al. conducted a study of the top hundred energy users in Taiwan from 2001 to 2004 that included the iron, steel, chemical, pulp, paper, textiles and electronic/electrical industries [14]. The recommendations on how to improve energy efficiency across the industries can be summarised as:

- Improve the efficiency of electrically driven rotating equipment such as compressors, pumps, kilns and fans by using VSDs.
- Recycle waste heat from high-temperature devices such as furnaces by installing air preheaters, steam recuperators and similar devices.
- Reduce waste heat by installing better thermal insulation.
- Convert waste heat to electricity.

A potential energy reduction of 5×10^8 litres of crude oil equivalent per year was estimated by Chan et al. for the industrial sector of Taiwan [14]. This reduction represents about 1% of the estimated industrial sector of Taiwan's annual consumption of energy for 2001 to 2004.

Martins reports the electricity use of an SAF in ferrochrome production to be 3 600 kWh/ton [15]. He cites Riekkola-Vanhanen who found the best practice electrical energy use to be 3 100 kWh/ton to 3 500 kWh/ton. His study lists energy reduction techniques and integration, as well as indicating practical ways of improving performance in an operating plant based on SAF technology. Martins specifically mentions efficient motors; the use of VSDs; pump, fan and lighting efficiency improvements; and furnace optimisation as ECMs to consider. He points out the importance of following an integrated process and energy improvement approach.

A study of energy efficiency improvement and CO_2 reduction potential in the Chinese iron and steel industry conducted in 2010 by Hasanbeigi et al. identified measures that could be implemented in the various unit operations [16]. Some of these measures are adopted in Chapter 3 of this study. Heat recovery was predicted by Hasanbeigi et al. to result in more than 50% of the potential savings. A 46% potential energy reduction was calculated for the industry. Hasanbeigi et al. found an emission factor of 0.77 kg CO_2 per kWh electricity generated by a coal-fired power plant.

Although based on copper production, an article by Warczok and Riveros contains useful information on energy requirements for various copper ore reduction unit processes [17].

Total energy requirements (combined fuel and electricity) vary from 19 GJ/ton to 43 GJ/ton copper produced for the seven copper production technologies evaluated. The following ECMs are mentioned in the article:

- Utilise the heat energy in liquid metal and slag to preheat raw material.
- Switch from a batch to a continuous process.
- Use less intensive refractory cooling.
- Recover heat from off-gas.
- Optimise compressor use.
- Preheat air for concentrate drying.

Letaba uses a coreless induction furnace (AlloyStream uses the term “inductor”) to maintain the liquid bath temperature. Giacone and Mancò measured the energy efficiency in a casting plant using coreless inductors for melting metal [18]. A method used to model the system, called the site energy system model, is described. Five components are used in the model: imported energy, energy generation system, energy carriers, energy utilisation system and energy drivers. A matrix representation of the energy system of a factory is presented by Giacone and Mancò with case studies. A simplified version of the matrix approach was used in this study. This technique should be considered as a key component of an energy management program for AlloyStream.

Energy flow analysis for three major energy-consuming mills of the pulp and paper industry in Taiwan (officially the Republic of China) is presented by the Chen, Hsu and Hong [19]. Many of the measures recommended are similar to those proposed by Hasanbeigi et al. [16]. The payback period of energy efficiency improvement measures is calculated by dividing the estimated capex required to implement the measure with the monthly predicted saving in energy cost. The same approach is used in this study.

A practical roadmap to improving energy use in a plant is presented by Hagemo [20]. He emphasises the importance of both the technical factors to consider and the psychological factors that can be important barriers or enablers for the implementation of ECMs. Hagemo also indicates practical ways of estimating energy use where a lack of energy measuring instrumentation exists.

A comprehensive publication by the European Commission’s Directorate-General Joint Research Centre discusses (in part) energy efficiency measures in smelting processes [21]. Where applicable the recommendations in the document have been adopted in this study, for example low-temperature coal drying with waste heat and off-gas heat recovery.

An Institute of Electrical and Electronics Engineers recommended practice for energy conservation contains valuable information on motors and lighting [22].

Some useful benchmark values are given in a comprehensive analysis of the USA iron and steel industry's energy use by Worrell, Martin and Price [23]. Energy used in the various unit processes are listed and compared with other regions. The report also lists ECMs that will improve energy efficiency - such as preventative maintenance, energy monitoring and management, VSDs, heat recovery, pulverized coal injection, pressure recovery turbines, heat recuperators, improved furnace insulation and combined off-gas gas turbine/steam turbine with steam injection in the gas turbine. The payback periods for various ECMs are estimated. Steam injection for gas turbines is offered as a commercial solution by Cheng Power Systems [24].

The US Environmental Protection Agency (EPA) Energy Star energy management process is described in a report by the Office of Air Quality Planning and Standards [25]. The report lists a large number of ECMs applicable to the iron and steel industry. The applicability, feasibility and estimated payback period of the measures are indicated and each measure is discussed in some detail.

Nored, Wilcox and McKee list waste heat recovery methods with basic calculations for Organic Rankine Cycle (ORC), SRC and gas turbines [26]. They found the capex of ORC systems to be between \$2 000/kW to \$2 500/kW and the opex between \$0.01/MWh and \$0.05/MWh. A relative ranking of the technologies against four criteria (capex, lifecycle cost, energy grade and effectiveness) is done.

1.3.3 Specific measures to improve energy efficiency

Barati et al. found that the metal and slag tapped from a furnace represent a significant energy stream [27]. A slag enthalpy of 1.6 GJ/ton for ferroalloys is indicated in their article. This value is close to the 1.4 GJ/ton value as used by the AlloyStream metallurgical department. The slag thermal energy can be recovered but the method is dependent on the slag cooling requirements. If the slag is intended for use in the cement industry, cooling has to be rapid to achieve a glassy state. The very low heat transfer coefficient of slag counteracts rapid cooling. Various means of rapid slag cooling, with the appropriate heat recovery techniques appropriate to the slag treatment, are described by the authors. A recovery of up to 65% of the thermal energy is predicted in the article by Barati et al. [27]. In this study a 50% recovery level is used.

The off-gas leaving the LP1 furnace represents a thermal energy rate of more than 3 MJ/s. Effective utilisation of off-gas is one of the most important measures to improve the energy efficiency of the plant. One method could be to employ an externally fired gas turbine (EFGT). Datta, Ganguly and Sarkar performed an energy and exergy analysis of an EFGT for three sets of pressure ratios, heat exchanger cold-end temperatures and turbine inlet temperatures [28]. A trade-off design was reached with a thermal efficiency of 26% under conditions similar to LP1’s off-gas.

An alternative to the gas turbine’s Brayton Cycle (BC) for the conversion of heat to power is the Rankine Cycle (RC). The RC, based on three different working fluids, has found application in waste heat recovery:

- Steam as working fluid (SRC)
- A two-part fluid (Kalina Rankine Cycle, or KRC)
- An organic fluid (ORC)

In a theoretical back-to-back comparison of a KRC versus an ORC, both with 1.8 MW output and utilising waste heat at 140˚C, the thermal efficiency of the KRC was found to be 6% versus 8.5% for the ORC [29].

Murrugan and Subbarao modelled a combined cycle consisting of SRC-top and KRC-bottom systems and found a first law efficiency improvement of 1.43% and a power increase from 82.2 MW to 83.6 MW [30]. A further benefit of this configuration is that the SRC condenser runs at above atmospheric pressure.

Water-cooling is used extensively on LP1 and as a result the plant rejects about 50% of the waste heat at 40°C to the environment through water evaporation. One option to improve the energy efficiency is to raise the cooling medium temperature and recover the waste heat at an elevated temperature. Little and Garimella compared various thermodynamic cycles to convert low-temperature waste heat (60˚C and 120˚C) to work and for cooling. They found the ORC to yield the best heat-to-power efficiency [31]. Heat transformers are also described. A basic description of the Maloney-Robertson Cycle to generate power is given. The Maloney-Robertson Cycle is based on the absorption-cooling cycle, modified to yield net power.

Chan et al. reviewed technologies suitable for low-grade thermal (<250˚C) energy recovery in the United Kingdom [32]. The ORC, Super-critical Rankine Cycle (SCRC), KRC, and Trilateral Cycle (TLC) are discussed with valuable metrics. The SCRC was found to have a marginally higher thermal efficiency than the ORC. The TLC is theoretically more efficient than both the ORC and SCRC, but it is not a commercial option at present. A large reference base is given. A similar study was performed by Ammar et al. that also covers the basics of heat pipes [33].

Waste heat can also be used to heat combustion air before entering the Letaba furnace. A regenerator that heats combustion air to between 900˚C and 1 200˚C by recovering heat from the exhaust gas (off-gas) of a glass furnace was studied by Sardeshpande et al. [34]. Fouling of the heat exchanger by dust caused a substantial deterioration in performance. The Letaba furnace operates at a gas temperature of 1 550˚C.

Stehlìk discusses heat exchanger design for flue gas at temperatures between 600˚C and 1 000˚C where severe fouling is present [35]. Some practical suggestions are given to improve heat transfer and reduce fouling under these conditions. In a similar study by the same author, more practical detail is given [36].

Shekarchian et al. conducted a thermodynamic and economic analysis on industrial-fired heaters [37]. The authors found that air preheating with off-gas would increase heating efficiency from 63% to 71%. The payback period for the high-efficiency gain options varied from 2.6 to 4.5 years.

An extensive list of low-temperature power cycles in operation worldwide are presented in an article by Ohman and Lundqvist [38]. Performance measures of operating systems are given. Heat source temperatures ranged from 60°C to 482°C and sink temperatures ranged from 4°C to 78°C. The fraction of Carnot efficiencies range from 0.05 to 0.65. The most promising cycles (ORC and KRC) were considered in this study.

An energy benchmark model developed for a glass furnace is described by Sardeshpande et al. [39]. The model is based on a rigorous mass and energy balance for the plant being studied. A potential reduction of 20% to 25% in energy use was predicted. The same method will be followed for the analysis of the entire Letaba plant (not only the furnace as was the case in the article) and in the development of an energy efficient alternative plant configuration.

In an article describing the development of conceptual optimal mine energy supply the authors list five constraints: energy conversion technology, installation (space), utility balancing, carbon monoxide (CO) emissions and energy market (financial) constraints [40]. Energy flow is depicted graphically in a superstructure diagram.

Some practical recommendations are given in a short article by Carpenter [41]. Three of the seven techniques that he discussed are applicable to this study. These techniques are the production of products to specification, reduced pressure drop across control valves, and design for energy efficiency the first time.

De Paepe et al. modelled a micro-gas turbine with steam injection generated with heat from the exhaust gas [42]. An improvement in the electrical efficiency of 2.2% was predicted when 5% of the air flow was replaced with steam.

Wang, Chiou and Wu analysed a simple gas- or oil-fuelled commercial gas turbine and determined the effect on power output and efficiency with inlet air-cooling and steam injection [43]. Both measures were generated with the waste heat from the gas turbine exhaust. They claim that the standard turbine efficiency is increased from 29% to 40% with inlet air-cooling and steam injection, and the power output increased from 53 MW to 92 MW. These gains are considerably more than what De Paepe et al. found. The authors did not specify how the substantial additional power would affect the gas turbine’s reliability.

An article by Reddy, Naidu and Rangaiah covers a broad range of waste heat recovery techniques in chemical process industries [44]. They list twelve practical criteria to be considered such as space, minimum temperatures and so forth. In particular they recommend that heat-to-heat recovery could be considered in preference to heat-to-electricity.

Iora and Silva conducted a theoretical analysis of an intercooled, externally heated, double shaft micro-gas turbine and found an electrical efficiency of 21% at a turbine inlet temperature of 750°C [45]. The turbine is based on an automotive turbocharger.

An energy and exergoeconomic analysis of a system using combustible blast furnace gas combined with sinter gas from a steel production plant was done by Yao et al. [46]. The combined gas stream fuels a combined cycle consisting of a gas turbine top cycle with a steam turbine bottom cycle. Three possible configurations were analysed and the optimum configuration from an energy, exergy and economic perspective (including capital cost) was found.

Externally fired micro-gas turbines with biomass as fuel were evaluated by Cocco, Deiana and Cau [47]. The high-temperature heat exchanger is the most expensive component of the system and poses the biggest challenge for thermal efficiency improvement. As expected, pressure ratio and turbine inlet temperature primarily determine the thermal efficiency. This was found to be 22% at a turbine inlet temperature of 800°C and 33% at 1 200˚C.

Snyman found that the efficiency of the compressed air supply at a South African gold mine can be increased substantially [48]. He recommends right-sizing the compressors, using high-efficiency compressors, high-efficiency motors and VSDs where feasible. His study has relevance since similar initiatives will be considered in this study.

Commercially available solar PV modules are now reaching a claimed conversion efficiency of 17% at a radiation level of 1 000 W/m^2 [49].

1.3.4 Articles that are classified as background

A Grasys product brochure gives information on two of three technologies for producing pure oxygen and/or oxygen-enriched air. These are vacuum and/or pressure swing absorption (VPSA) and membranes [50]. The use of these two technologies could substantially reduce the oxygen enrichment cost of Letaba. Oxygen generation with VPSA or membrane technology is discussed in Chapter 6 of this study.

A low-cost modelling method to identify and quantify the potential for energy reduction in a fired plant (furnace) is described by Tucker and Ward [51]. The zone method will be useful to perform a basic heat transfer calculation of the Letaba furnace internally, but is not in the scope of this study.

An article by Sano, Mizukami and Kaibe describes work done by Komatsu to improve the efficiency of thermoelectric generation (TEG) modules [52]. By optimising the production process the thermal efficiency of a low-temperature module was improved from 6% to 7%. This efficiency was reached at a ΔT of 250°C. An overall efficiency of 6% was predicted when the inverter losses were included. By comparison a supplier of commercially available TEG modules [53] states a realistic overall efficiency of 3% at a ΔT of 200°C. Phillips found an efficiency of 7% at a ΔT of 100°C, with a theoretical efficiency of up to 18% [54].

Chen, Chung and Liu analysed the energy use and performance of steel billet reheating furnace (gas-fired) in a hot strip mill [55]. They found that 48% the off-gas heat could be recovered in the furnace.

An energy and exergy assessment of a lime kiln by Gutierrez et al. serves as a valuable comparison and guide to analysing the reduction process performed in the Letaba furnace [56]. In the study 50% of the energy loss in the kiln was found to be due to combustion, heat and momentum transfer and loss to exhaust gases.

Above-inflation increases in electricity cost will have a negative impact on the competitiveness of ferroalloy producers, as electricity is a substantial operating cost component. In the presidential address to the Southern African Institute of Mining and Metallurgy in 1980, Dr Jochens commented on the effect energy cost has on ferroalloy producers (including ferromanganese) in South Africa [57]. Dr Jochens stressed the risk posed by such cost increases and warned that this could lead to ferroalloy producers moving their facilities to countries with lower electricity rates. In 2013 Assore announced that they were to move their ferromanganese production facility to the Philippines, citing lower electricity rates as one of the reasons [5].

Mahto and Pal explored the efficiency of a dual combined cycle with a gas turbine top and steam Rankine bottom. Six steam turbine configurations were modelled. The highest efficiency was obtained with the triple pressure steam turbine combined with inlet fogging of the gas turbine. At a gas turbine pressure ratio of 20:1 the thermal efficiency exceeded 50% [58].

Significant opportunities for energy reduction were identified by Matsuda et al. by applying pinch analysis in the evaluation of energy use at a large steel plant [59]. They found that 21.2 MW can be generated by optimizing the heating and cooling systems with the technique.

In an article on the history of pyrometallurgy Habashi lists technological changes from the start of civilisation to present [60]. The fascinating list of technological advances starts with the ancient Egyptians who used bellows to generate air blasts. Next the water wheel became a source of power, followed by the replacement of coal with coke in 1735. In 1856, another major breakthrough came when Bessemer and Kelly on both sides of the Atlantic developed a technique to produce steel from pig iron.

Jegla describes the conceptual design of a tubular furnace with typical heat flues values [61]. This could be useful for process optimisation inside the Letaba furnace and for off-gas heat recovery heat exchanger design.

An article by Sano covers power generation plants of TEPCO, a Japanese electricity producer [62]. TEPCO uses the SRC (47% efficiency), and the Brayton-Rankine combined cycle (61% efficiency) to generate power. The combined cycle plants use coal gasification. The turbine inlet temperature is as high as 1 600°C. A list of power plants and performance measures are presented.

Various commercially available process technologies are described and evaluated by Riekkola-Vanhanen in a comprehensive report on operating plants producing nickel [63].

Although not directly applicable, the method of analysis is instructive and the metrics valuable to this study.

An optimisation algorithm to find the best overall energy management strategy for combined heat and power system with district heating and thermal storage is described by Reverberi et al. [64]. A summary of pinch analysis is given in the study.

The performance of a small (1-5 MJ/s) pressure coal gasification system coupled to either a gas turbine or an internal combustion engine with syngas storage is described by Cau, Cocco and Serra [65]. The energy conversion efficiency of the coal-to-syngas component is reported as 80%. The gas-to-electricity conversion efficiency of the gas turbine engine was 27% at peak load with a corresponding 40% for the internal combustion engine. This study is relevant for the option of self-generation of electricity by leveraging the coal supply and infrastructure of FCP.

Engelbrecht tested low-grade coal in a pilot scale low-pressure fluidised bed gasifier [66]. Syngas with a lower heating value (LHV) of 3 000 kJ/kg was produced with a fixed carbon conversion between 55% and 85%.

Vera et al. compared a biomass to gasifier to syngas to micro turbine process with a biomass to externally fired micro turbine process, the biomass being generated by the olive oil industry [67]. The gasifier gas/turbine combination gave an efficiency of 12.3% and the EFGT configuration gave an efficiency of 19.1%

The need for self-generation is driven by the need for deployment of the AlloyStream^{TM} technology in areas where grid power may not be available, but also by the rapidly escalating grid power cost as reported by MarketLine for South Africa [68]. Eskom’s market share in 2011 of the South African electricity market was 98.8%. Income from electricity sold increased from R42.5bn for 2007 to R72.5bn in 2011, whilst volume sold reduced from 220 TWh in 2007 to 214 TWh in 2011. Unit revenue increased from 19c/kWh to 33.9c/kWh over the same period.

Weisbach et al. calculated energy returned on investment (EROI) values and other performance measures for various power generation systems (gas-fired turbines, solar PV, solar thermal, wind power and hydropower) [69]. The methodology to calculate EROI is explained.

An article by Akiyama et al. compared the recovery of waste heat from slag with two chemical processes or conversion-to-power or generating hot water. The authors found that methane reforming and producing cement from limestone and slag utilise the exergy of the slag more efficiently than generating steam or hot water [70].

A combined triple cycle with BC top, steam RC middle and ammonia RC bottom was analysed by Marrero et al. [71]. A ΔT of 10°C between the gas turbine outlet and steam middle cycle was used in the model. A thermal efficiency of 60% was predicted at a turbine inlet temperature of 1 800 K. Operating the steam condenser at atmospheric pressure is an advantage in addition to the high cycle efficiency.

Beloglazov et al. modelled a coal gasifier integrated with a gas turbine with water injection after the compressor. Two configurations were considered, both yielding thermal efficiencies in excess of 50% at a gas turbine pressure ratio of 30:1. A regenerator was included in both configurations [72].

Horlock covers the theory of water injection into a gas turbine fitted with a regenerator, focusing on the effect on the heat exchange in the regenerator. Two-stage injection is expanded to multiple injection sequences. The author found that water injection changes the performance of the gas turbine favourably. No specific examples or case study are presented [73].

An article by Tchanche et al. reviews applications of ORC technology. In geothermal to power applications efficiencies of 10% to 12% are reached with source temperatures of 130°C to 160°C [74]. In solar thermal application similar efficiencies are reported. Solar ponds with ORC, solar thermal and ORC with reverse osmosis and solar assisted cooling systems are also included in the article.

1.3.5 Evaluation

The literature survey revealed a wide range of technologies and techniques that could be considered to improve the Letaba plant’s energy efficiency. These measures, or ECMs, are not all at the same level of development. The author was fortunate to visit a number of suppliers in the USA and Europe in February 2013 to gain firsthand information on commercially available equipment:

- Flexenergy in Portsmouth, New Hampshire manufactures a 250 kW gas turbine generator set that can be configured as an EFGT. Only one of their units has to date been supplied to a client in Europe for EFGT evaluation.
- Elliot in Jeanette, Pennsylvania is a large manufacturer of steam turbines in the power range applicable to Letaba.

- Cool Energy in Boulder, Colorado has developed a 3 kW low temperature Stirling engine that is currently undergoing reliability testing. They are developing a 20 kW unit.
- LA Turbine in Valencia, California manufactures turbo-generators and turbo-expanders.
- Mavi-Trench in Santa Maria, California manufactures ORCs, turbo-generators and turbo-expanders.
- Turboden in Brescia, Italy manufactures ORCs. A 1 MW operating ORC was visited. Over 200 Turboden ORCs are in service worldwide.

The Handbook of Energy Systems Engineering [11], although printed in 1984, proved invaluable in guiding this research, as did The Energy Management Handbook by Dowty and Turner [12]. Most of the articles found were via the online search facility of the North-West University. The main journal sources were Energy (9), Applied Thermal Engineering (7) and Applied Energy (6). The US EPA website and dissertations and theses from the University of Pretoria and the North-West University also proved valuable.

It is clear that not a single technique or technology should be considered in the conceptual design of an energy efficient plant, but rather a range of technologies. Examples are improving the efficiency of the conversion of energy by existing devices such as electric motors to convert waste heat to power by adding additional devices such as a heat exchanger and an ORC.

Significant variations in performance of the measures are observed in the literature. In this study the more conservative values were used where more than one value was presented.

1.4 Problem statement and objectives of this study

The key problem addressed in this study can be stated in three parts, being:

1. How can the energy efficiency of the ore reduction plant on which the study is based be measured?
2. Which is the best way of improving the efficiency?
3. To what level can it be improved?

Question 1 is addressed in Chapter 2, Section 2.6. Chapter 3 identifies ways to improve the efficiency, thus answering Question 2. Chapter 4 answers Question 3 where the improvement in efficiency of the Letaba plant is indicated.

The problem statement can be reworded as two hypotheses:

1. Hypothesis 1 – the energy efficiency of the plant can be determined (or calculated or measured) by measuring the output work and input energy.
2. Hypothesis 2 – the energy use of the plant can conceptually be reduced by more than 5 000 MJ/ton by implementing a number of appropriate ECMs.

Hypothesis 1 is addressed in Chapter 2, Section 2.6. Hypothesis 2 is addressed in Chapter 4.

The energy reduction as stated in Hypothesis 2 was estimated at an early stage of the study. At the design stage of LP1 it was known that the waste thermal energy in the off-gas is more than 3 MJ/s at a maximum temperature of 1 800 K. However, the maximum temperature that can be handled by commercially available materials from which a heat exchanger can be constructed is 1 400K continuously [75, 76]. From Wall the maximum heat-to-work efficiency that can be attained from the heat source, according to the second law of thermodynamics, is:

Equation 1: Second law efficiency

$\eta = 1-(T_o/(T-T_o).\ln(T/T_o)$ for $T = 1\ 400$ K and $T_0 = 300$K: $\eta = 0.58$

Typical fraction of Carnot efficiencies in such an application is 40%. Therefore the expected efficiency is:

$0.4 \times 0.58 = 0.23$ giving an expected electrical power that can be generated from the thermal energy in the off-gas of 690 kW or 2 322 MJ/ton.

It was also known that the total energy rate into the plant was in the order of 14 MJ/s and that significant savings in areas other than off-gas may be possible.

The objectives of this study are to:

1. Identify and understand measures that can be applied to Letaba in order to improve the plant's energy efficiency (Chapter 3).
2. Map the energy flow to and through the AlloyStream Letaba plant (Chapter 4).
3. Determine the energy efficiency of the Letaba plant as it exists (Chapter 4).
4. Select appropriate technologies and complete a conceptual redesign of the plant (Chapter 4).

5. Verify the predicted benefits of two efficiency conservation measures implemented on Letaba (Chapter 5).
6. Recommend research and development that could result in further gains in energy efficiency and plant effectiveness (Chapter 6).
7. Prove or disprove the two hypotheses.

1.5 Methodology

The primary methodology followed in this study is process modelling. In-plant testing of the ECMs is the preferred way to verify the performance predicted by the model. Unfortunately it is impossible to test the list of ECMs conceptually implemented in practice, given time and resource constraints. Two measures could fortunately be verified through testing during the study. They are discussed in Chapter 5. For the ECMs conceptually implemented the focus was on verifying the information sources and the spreadsheet accuracy.

Supporting the conceptual design is a spreadsheet that models the various plant configurations described. The accuracy of the data was assured by:

- Observing actual values on the Letaba plant.
- Calculating data from primarily fundamental thermodynamic and heat transfer relationships.
- Using data from reputed publications.
- Obtaining estimates from experienced and reputed specialists on the topic.

This study is normal applied research. Approximately 20% of this study is based on prototyping, being the two energy efficiency measures described in Chapter 5. They could be deemed prototypes, even though they are in full-scale operation, because Letaba is in itself a prototype of the commercial plant. The remaining 80% is a mixture of primarily quantitative methods based on basic numerical modelling and qualitative methods.

The process followed to arrive at a conceptual design of an energy efficient plant is based on the problem-solving approach described by Athey [77]. His approach consists of the following steps:

- Formulate the problem to be addressed (Section 1.4).
- Define the system within which the problem appears, as well as its boundaries and its environment (Chapter 2).
- Define scenarios within which the solution or solutions must be viable (Chapter 2).
- Set objectives to be achieved with the study and the planning horizon (Chapter 2).

- Describe the existing system and key interrelationships (Chapter 2).
- Set performance metrics (Chapter 2).
- Set constraints and criteria (technological, economic, psychological, political) (Chapter 2).
- Develop alternative solutions, in this case ECMs that meet the constraints (Chapter 3).
- Evaluate alternatives (Chapter 3).
- Select the best solution (Chapter 4).

A flow diagram of the problem-solving approach is depicted in Figure 1.

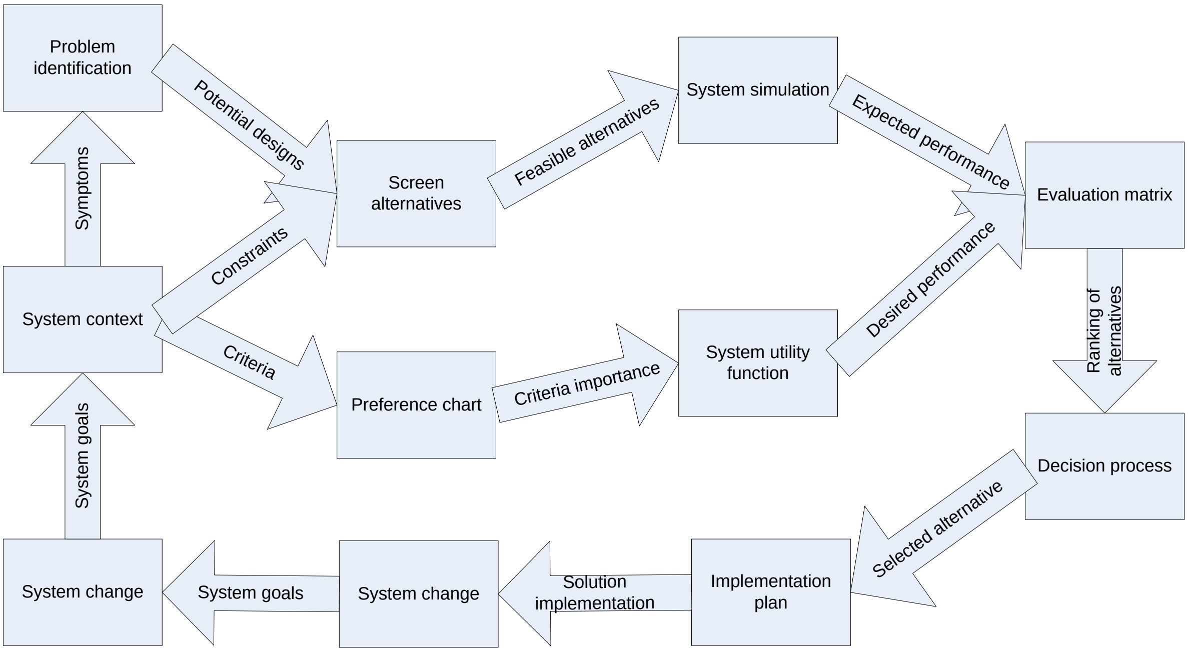

Figure 1: Flow diagram of the systematic problem-solving approach

This study will deviate somewhat from the process described by Athey for the following reasons:

- A full analysis is beyond the scope of this study.
- The process described by Athey focuses on mutually exclusive solutions. In this study a number of ECMs that will improve the plant's efficiency have been identified – actions that are not necessarily exclusive or independent. The challenge is to find the combination of ECMs that results in the most energy efficient plant within the bounds of the constraints and with due consideration to the criteria.

To reduce complexity the number of scenarios will be limited to two. Scenario 1 will apply to the AlloyStream Letaba demonstration plant in its location as in 2013. Scenario 2 applies to the first commercial plant, located next to an ore body with start-up in 2023.

Some of the information in this study is based on observations by the author in his capacity as the leader of the AlloyStream engineering department from 2006 to present. During that time the engineering department completed a concept design on a commercial plant and designed and constructed Letaba. The team typically consisted of five graduate engineers, five technicians and three engineering assistants.

1.6 Overview of this document

This study takes the reader through a series of steps aimed at answering the three key questions - how to measure the energy efficiency of the Letaba plant, how can it be improved and to what level. The problem-solving process described by Athey will be followed throughout.

Chapter 2, Section 2.6 answers the measurement question, states the relevance of the problem to AlloyStream, and describes the scenarios, constraints and criteria that potential and feasible solutions are subject to. In Chapter 3 potential solutions or ECMs are analysed and their standalone relative worth determined by applying the criteria developed in Chapter 2. The ECMs with the highest relative worth are applied conceptually to the existing plant in Chapter 4. This leads to a more efficient plant configuration. In Chapter 5 the results from two ECMs that have been implemented to date are discussed. They are a low-pressure blast air system and a constant high-ΔT water-cooling system. Chapter 6 concludes the study by predicting the potential energy efficiency of a commercial plant, given ten years of technology development. Recommendations on further research to enable the predicted gains in efficiency to be realised are also made.

1.7 Conclusion

The development of the AlloyStream^{TM} pyrometallurgical ore reduction process has reached the commercialisation stage. Plant-wide energy efficiency improvement and energy cost reduction can significantly change the product's market appeal. This study was initiated by AlloyStream to find answers to the three questions posed in Section 1.4.

From the literature study it is clear that substantial improvement in the energy efficiency is possible and that a host of various measures should be considered for implementation.

CHAPTER 2

In Chapter 2 the relevant characteristics of ore reduction plants are discussed; particularly the characteristics of the plant used as the object of this study. Plant energy efficiency measurement is discussed. The scenarios within which the existing plant and future plants will operate are sketched. Constraints applicable to potential measures to improve the existing plant's efficiency and criteria that will be applied to select feasible measures are developed.

The aim of education should be to teach us rather how to think, than what to think — rather to improve our minds, so as to enable us to think for ourselves, than to load the memory with thoughts of other men. ~Bill Beattie

2 Ore reduction plants and the plant selected as a case study

2.1 Overview

Smelters produce metals through ore reduction at a high-temperature. The process involves mixing ore with a reductant (such as coal), elevating the temperature of the mix in a furnace to reduce the ore to metal; extract, clean and discard the flue gas, tap and separate the metal and slag, and refine the metal product to industry standards (Section 2.2).

The Letaba plant is a culmination of many years of research and development. It is essentially a prototype for commercial plants that should enter the market within the next ten years. Energy efficiency can be a competitive advantage, hence the importance of this study to the sponsor (Sections 2.3 and Section 2.4). A basic description of the plant is given in Section 2.5. In Section 2.7 two scenarios are presented, the system context briefly discussed and the constraints that solutions will have to meet listed. Hypothesis 1 is also assessed in Section 2.6. Finally four evaluation criteria and a system utility function are developed in Section 2.8.

Figure 2: Letaba furnace

2.2 Relevant characteristics of pyrometallurgical ore reduction plants

Pyrometallurgical ore reduction plants generally consist of the following sub-systems: raw material handling, furnace or furnaces, metal and slag handling, off-gas handling, water-cooling, gas distribution, electricity distribution, waste heat recovery, control and instrumentation, buildings, cranes and other support systems. The furnace is the most energy intensive sub-system.

Ore, reductant and fluxes are received, prepared, mixed and charged to the furnace in batch form or continuously. In the furnace the feedstock is heated to a high temperature to enable the reduction process. Metal and slag are removed from the furnace as a batch (called tapping) or continuously. The molten products may leave the furnace separated or in a combined stream, as is the case with Letaba. The liquid metal and slag are poured from the furnace into a vessel designed to contain the high-temperature liquid. If the vessel is used to convey and separate the liquid metal and slag it is called a “ladle” and if the metal and slag are allowed to solidify in the vessel it is called a “mould” or a “slag pot”. In moulds the liquid metal and slag are allowed to separate, solidify and cool.

The product-handling system separates metal and slag from the moulds and processes both to the standard required by clients. Typically the composition, purity and particle size are specified for metal. For slag the composition, particle size and metal entrainment are specified.

A typical reduction process is the reduction of manganese and iron oxides to high carbon ferromanganese containing 76% manganese (Mn), 16% iron (Fe) and 8% carbon (C). The ore consists of various manganese oxides, ferric oxide (Fe_3O_4), silica (SiO_2), alkali oxides, and carbonates (CO_3). A series of reduction reactions starts at about 400°C with the final reaction (MnO to Mn) requiring a temperature above 1 250°C [1].

Pure manganese oxide is not found in nature. Invariably the manganese oxide is mined with sand, iron oxide and other chemical compounds, resulting in a typical manganese content of 25% to 45% by mass in the ore. The reduction process also does not extract all of the manganese in the ore. The percentage recovery is dependent on a number of factors such as the temperature of the reaction zone, the carbon monoxide concentration, how well the reductant and ore are mixed, and the particle size and chemical characteristics of the ore and reductant.

The main types of furnaces used for ferromanganese production are SAFs and blast furnaces. There are many other types of high-temperature furnace from where measures to improve energy efficiency can be learned. To name a few:

- Open electric arc furnaces.
- Vacuum furnaces.
- Induction furnaces, mainly used for melting of metals in casting plants.
- Basic oxygen furnace used for reducing the carbon content of metals.
- Coke furnaces used for converting coal to coke.
- Refinery (reforming) furnaces used for cracking of hydrocarbons.
- Other furnaces used for reheating of, but not liquefying, materials or metals.
- Glass furnaces in which silica is turned into glass.
- Waste burning furnaces, or incinerators.
- Cement kilns.
- Furnaces used for the generation of steam (boilers).

The term “furnace” is derived from the Latin word “formax”, meaning oven. In this study the term is used for a vessel in which an internal temperature in excess of 1 000ºC (1 273 K) is reached during normal operation.

Broadly speaking, furnaces are powered primarily by electricity, chemical energy or by a combination of electricity and chemical energy, as is the case with the Letaba furnace.

A substantial amount of energy is required to generate and maintain the elevated internal temperature often requiring a fuel source in combination with oxygen enrichment of air or pure oxygen. Heat is rejected to the environment as waste energy, both through the furnace walls to the cooling system or surrounding air, to the off-gas and to the environment as the metal and slag tapped from the furnace cools down.

Some or all of the parts of a furnace shell require intense cooling to maintain structural integrity. The walls of the furnace and off-gas ducting are usually cooled with forced air, water film, pressurised water jackets or spray-cooling with water. Where water-cooling is employed the water temperature is kept below 60ºC to reduce scale formation. This makes heat recovery from the cooling water impractical. The heated water is usually cooled through evaporation, with evaporation rates in the order of 1 kg water for every 2 000 kJ of waste heat rejected. Water-cooling appears to be a low capital cost, highly effective method of cooling, but the hidden costs, such as pump power and make-up water cost can be significant.

This study focuses on AlloyStream's Letaba prototype plant for the production of ferromanganese. The plant is described in the following sections.

2.3 The history of AlloyStream

The development of the AlloyStream^{TM} technology started in the last decade of the previous century when direct reduction of iron ore was tested in a liquid iron holding furnace in the then Iscor's Newcastle plant. Bench-scale testing eventually culminated in the first commercial plant being built in Iscor's Vereeniging Works. This plant had to be shut down due to a system failure during commissioning in 1999 and was subsequently decommissioned without producing any steel from iron ore.

After comprehensive reassessment, a process model applicable to ferromanganese production was developed. A small test furnace with related support systems was constructed in Pretoria to validate the process model and test various refractory and other hardware configurations. HC FeMn was successfully produced over three campaigns (or production runs) in this test facility named Rivet. Campaign durations were from three to five months.

In 2006, AlloyStream intended to proceed with designing and building their first commercial plant. Due to the sub-prime financial crisis of 2008/2009, which caused the selling price of HC FeMn to drop from $2 300/ton to $800/ton, a lower cost pre-commercial proposal was accepted. The proposal was based on a substantial upgrade of Rivet. In 2009, funds were obtained for the upgrade but due to financial constraints most of the existing equipment was reused and plant energy efficiency could not be substantially addressed.

The upgrade entailed increasing the design output of the Rivet facility from 220 kg/hour HC FeMn to 1 070 kg/hour by modifying some existing sub-systems and replacing others with larger sub-systems. In the case of the furnace, the internal diameter increased from 2.5 m to 5.3 m necessitating a new shell, a new refractory lining, a new water-cooled system, a completely new off-gas handling system and other less important changes.

Letaba started its first production run (or campaign) in February 2012. By October 2012 it produced more than 3 500 ton of HC FeMn. In October 2012 the furnace had to be shut down due to a premature furnace refractory failure. From October 2012 to July 2013 the refractory was replaced and some modifications made to the plant. Letaba campaign 2 started in August 2013 and is underway at the time of print.

The Letaba plant serves a number of purposes:

- It demonstrates the AlloyStream^{TM} process technology
- It enables plant-wide technology development, including equipment reliability improvements
- It enables process operation and equipment maintenance knowledge growth

2.4 Relevance of this study to AlloyStream

The technology being developed by AlloyStream to produce HC FeMn competes with technologies that have been around for more than a century [79]. Some of the advantages of the AlloyStream^{TM} technology are that the electrical energy use per product ton is substantially less than that of existing technology, and small fraction ore can be processed.

The three main energy streams into Letaba are electricity at 100c/kWh (or 28c/MJ), fuel gas (natural gas supplied by SASOL) at 7.1c/MJ, and coal at 2c/MJ (excluding the transport cost for coal). This ratio is expected to stay fairly constant over the next two decades. It would therefore make economic sense to reduce the use of electricity from the grid by firstly converting as much as possible waste heat to electricity, and secondly burning additional coal to generate the balance. This study focuses on the first part of such a strategy. The self-generation option is explored in Chapter 6.

Energy cost (not necessarily consumption) is a key factor in deciding the economic feasibility of a smelter. AlloyStream aims to enter the market by 2018 and therefore must use the time and facility available to at least demonstrate, on a pilot basis, ECMs that will be incorporated in future commercial plants.

In addition, technology in the energy sector is developing rapidly. An example is PV technology where the conversion efficiency is increasing and the unit cost reducing consistently [78]. A similar trend can be identified for heat-to-power conversion cycles such as KRC and ORC, hence the importance of incorporating energy management, not only at the existing plant, but also at a company level. In this regard ISO 50001 is a comprehensive energy management standard that aims to achieve continual energy improvements [80]. This study could be an important step for AlloyStream to become ISO 50001 compliant.

2.5 Description of the Letaba plant

A simplified process flow diagram of the Letaba plant is shown in Figure 3 below.

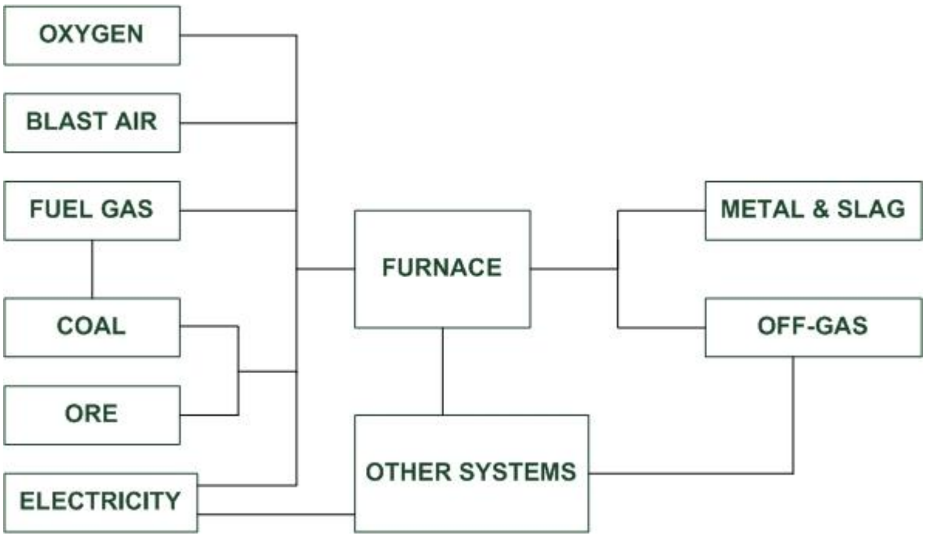

Figure 3: Simplified process flow diagram of the Letaba plant

Ore is transported by truck from mines in the Northern Cape over a distance of 640 km to the Letaba plant. Coal is also transported by truck over a distance of 80 km from mines in Mpumalanga. Oxygen and fuel gas arrive via pipelines; electricity is supplied by the local municipality who is in turn is connected to the national grid.

Electrical energy is used throughout the plant. The main electrical loads are the inductor (maximum power 2.5 MW), the air compressors (maximum power 500 kW), the water-cooling system (maximum power 245 kW) and the off-gas system (maximum power 85 kW).

The plant produces metal from ore as follows:

- Ore and coal is received, stored, the coal is dried and the ore and coal are mixed and fed to the furnace by the raw material handling system.
- The ore and coal mixture is introduced into the vessel through feed ports in the furnace roof. The feed mix falls through the combustion chamber onto heaps that float on the liquid metal bath in the lower part of the vessel.
- The liquid metal bath is heated with induction using electrical energy. Some of the thermal energy from the metal bath is transferred through the slag layer to the heaps.

- In the heaps most of the ore is reduced to metal by fixed carbon and carbon monoxide gas from the coal. Some carbon monoxide is released to the upper part of the furnace and combusted. Metal moves down through the slag layer into the metal bath.
- Fuel gas and oxygen-enriched air are injected into the combustion chamber; the resultant exothermic combustion reaction transfers heat to the heaps.
- The combustion products (off-gas) leave the vessel at high temperature.
- Slag and metal are tapped from the vessel through tapholes and allowed to solidify and to cool to ambient temperature.

A simplified process flow diagram for the Letaba furnace is shown in Figure 4.

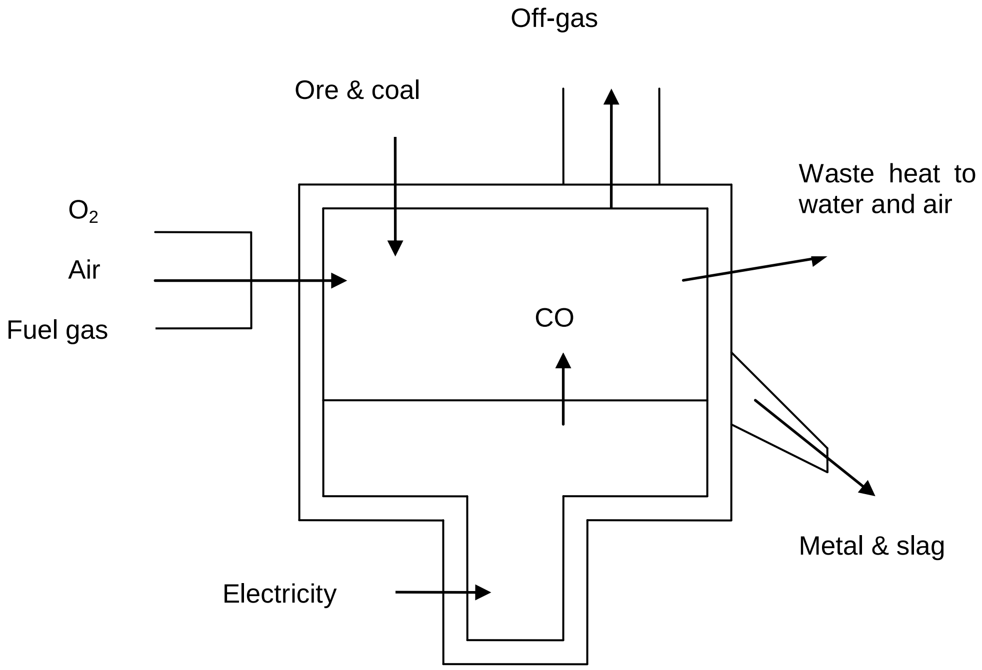

Figure 4: Simplified process flow diagram of the Letaba furnace

The key points of this study relating to the furnace are:

- The reduction energy represents approximately one third of the energy entering the furnace, another third is removed by the cooling water and air, and the balance consists of off-gas, and metal and slag thermal energy.
- The internal temperature is not allowed to drop below 1 400°C to prevent refractory deterioration, even if no metal is produced. The result is that the consumption of oxygen, fuel gas and electricity does not vary much with changes in production rate.
- The liquid bath has a high thermal capacity of approximately 213 GJ.

- Metal and slag are tapped in batches from the furnace every two hours.

The energy use of the whole plant (LP1) as designed is given in Table 1. The data is from the baseline design documents, being the process functional requirements (PFR) and process flow diagrams (PFDs).

Table 1: Energy use of LP1 as designed

Energy source	Conversion/use	% of total plant energy	Mean energy use per ton metal (est.)
Coal	Reduce ore and combust with oxygen to heat combustion zone	55%	26 968 MJ/ton
Electricity	Heating of metal bath by induction	9.7%	4 747 MJ/ton
Electricity	Inductor drive and coil losses	5.1%	2 486 MJ/ton
Electricity	Drive motors, coal dryer	0.1%	40 MJ/ton
Electricity	Drive motors, raw material batching and mixing and transport	0.4%	152 MJ/ton
Electricity	Gas extraction and dilution air	0.6%	286 MJ/ton
Electricity	Furnace forced air-cooling	0.3%	118 MJ/ton
Electricity	Pumps and fans	1.7%	824 MJ/ton
Electricity	Blast air from compressors	2.5%	1 225 MJ/ton
Electricity and fuel gas	Metal and slag processing and mould drying	8.1%	3 977 MJ/ton
Electricity	Lighting, uninterruptable power supply and offices	1.7%	841 MJ/ton
Fuel gas	Combusts with oxygen to heat the combustion zone	14.1%	6 857 MJ/ton
Diesel fuel	Powers mobile equipment	0.8%	370 MJ/ton
Total energy input		**100.0%**	**48 891 MJ/ton**
Total operating electrical load		**22.3%**	**10 863 MJ/ton**

2.6 Plant energy efficiency measurement

Most published work on energy efficiency in ore reduction plants appear to focus on improving the energy efficiency of the furnace, thereby improving the ratio of reduction energy to total energy used in the plant. In this study reduction energy is defined as the increase in enthalpy of the products due to the plant processes. Waste energy from the furnace is primarily heat loss through the furnace walls, heat loss due to hot gas (off-gas) leaving the furnace, and cooling of metal and slag.

In this study the approach is slightly different. The whole plant is viewed as a heat engine that converts input energy (primarily chemical and electrical energy) to work. The metal produced represents the useful output, or work. At a high level the plant can then be depicted as a thermodynamic system with the energy efficiency defined as work divided by energy in.

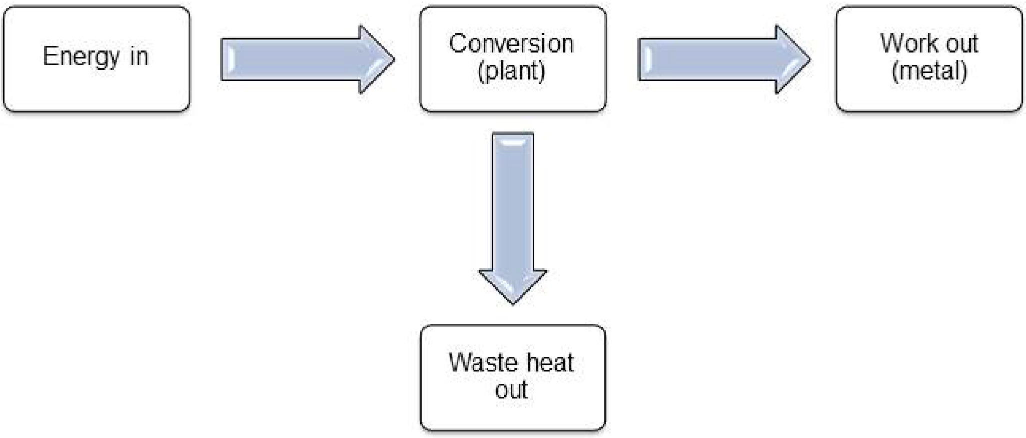

Figure 5: Plant depicted as a thermodynamic system

Although a large portion of the energy entering the existing plant is converted into heat in the furnace to drive the reduction process, the support processes are also substantial energy users, and significant gains in energy conservation were found feasible in those areas.

The metallurgical process parameters are given and accepted as a constraint, which is that energy efficiency measures must not negatively affect the metallurgical process. This constraint means that some potential solutions were not considered.

The first part of the problem statement - how to measure the energy efficiency of the plant – must be answered in order to prove Hypothesis 1. In general terms, efficiency is the ratio of useful output to input required to generate the useful output. For energy efficiency this is work from a system divided by energy into the system. For a thermodynamic cycle it is net work over heat supplied [81, 82]. The shaft power is, for example, the useful work produced by an internal combustion engine and for a power generator it is the electric power produced by the generator. Both shaft power and electricity are exergy.

It follows then that the exergy of the product produced by the plant should be the useful output expressed in energy terms. When this approach is applied to the reduction process it seems that the useful work performed is the exergy of the metal (if slag is classified as waste) or the exergy of both metal and slag (if slag is also deemed a product). In this study both the metal and slag will be defined as the product, as the slag from Letaba is classified as a by-product by the licensing authorities. The challenge is to determine the product exergy. Wall applied this approach to calculate the exergy of iron produced by the Swedish steel industry, and found it to be 6.91 MJ/kg [10]. The exergy efficiency, mining included, is 21%. The efficiency was determined by dividing the exergy of the iron produced by the energy required to mine and reduce the ore to iron. In equation form:

Equation 2: Efficiency

$\eta = E_{ex}/E_{in}$

Where:

- E_{ex} is the exergy of the iron produced
- E_{in} is the energy to mine and reduce the iron

The author believes that the method followed by Wall is the most fundamentally correct way of calculating the plant work output. However, a similar calculation for HC FeMn and slag is beyond the scope of this study.

An alternative approach is to calculate the minimum enthalpy required to produce the product. This was done by Tangstad and Olsen, who arrived at a value of 2 174 kWh/ton (7 830 MJ/ton) for a typical ore with 10% moisture content and 1 495 kWh/ton (5 382 MJ/ton) for an optimised ore mix with a moisture content of 5% [1]. The enthalpies of reactants and products are at the reference state, 298K, and only the metal produced is considered the product.

The process energy calculation by AlloyStream includes the enthalpies of the metal and slag at the bath temperature. If the calculation is adjusted to reference state a value of 2 133 kWh/ton (7 679 MJ/ton) is found. This correlates with the value for typical ore found by Tangstad and Olsen [1].

Deciding what the energy input to the plant is not as straightforward as it seems. The industry standard for the furnace is not clear – BHP Billiton and Assmang consider the electrical energy input only, whilst AlloyStream considers both electrical and coal as energy inputs, but not oxygen. In this study the rule "if it enters the plant and is significant, include it" was followed. Here significant means any energy stream that exceeds 20 kW averaged over 24 hours, therefore solar energy should be included: a controversial approach. The problem becomes more complex if the boundaries are moved upstream to include for instance the point where the reductant and ore is mined. Should direct solar power be included for the mines? Is the electricity entering the plant generated by burning coal or is a mix of technologies used? Questions like these are beyond the scope of this study, but they are important. In order to improve the understanding of the effect of the plant on the energy use in the plant's environment the study ventures somewhat outside the boundaries of the plant to include estimates of:

- Energy to mine ore and coal
- Energy to transport materials
- Coal-to-electricity conversion, assuming a coal-fired power plant
- Energy required to generate oxygen
- Solar energy entering the plant (the only solar energy considered)

In figure 6 these energy flows are presented in diagram form.

The author arrived at the conclusion that the plant energy efficiency can be measured – Hypothesis 1 is true. As calculating the exergy of the product is beyond the scope of this study the work produced by the plant will be taken as the process enthalpy from Tangstad and Olsen for the production of metal from typical ore, i.e. 2 174 kWh/ton metal, or 7 830 MJ/ton metal. Two plant input energy values will be used to calculate two plant energy efficiencies. The first input energy value will not include solar radiation and is abbreviated as G2GEE1 (gate to gate energy efficiency). The second input energy value includes solar radiation and is abbreviated G2GEE2. A third efficiency value, called the source to gate energy efficiency, or S2GEE will also be calculated. To calculate S2GEE the energy input to the ore and coal mine, transport energy, energy to produce electricity and oxygen will be included in the denominator. This answers Question 1 of the problem statement (How can the energy efficiency of the existing plant be determined?). Figure 6 displays the significant energy streams included in the calculations. The plant efficiencies determined in this study is reported in Chapter 6.

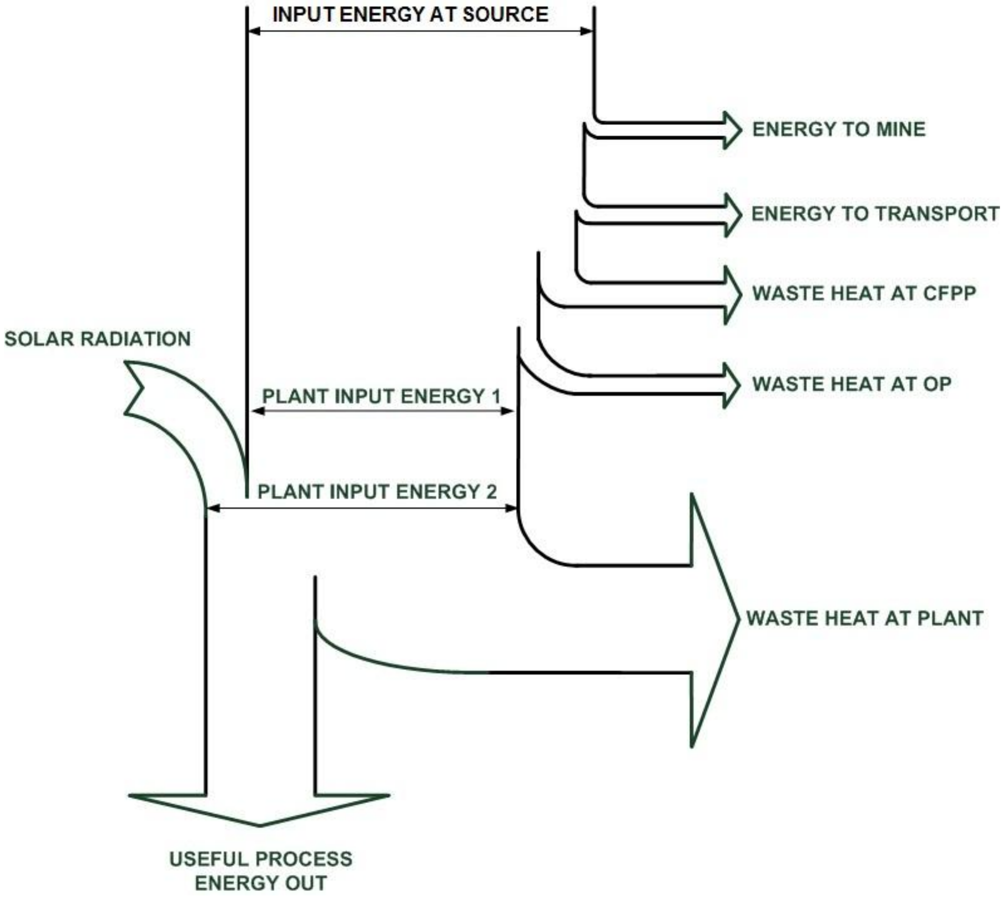

Figure 6: Simplified Sankey diagram of system energy flow

2.7 Scenarios, system context and constraints

The term “scenario” is defined by BusinessDictionary.com as a situation postulated by someone. The situation is based on assumptions and variables [83]. The purpose of the two scenarios used in this study is to describe the relevant assumptions made by the author in broad strokes and to identify important factors that the author believes currently do, or will affect LP1, LP2 and FCP in future.

2.7.1 Scenarios

Scenario 1: LP1 and LP2

- The plant is located in Pretoria West.
- Funding for testing of ECMs is available.
- Water is available at a cost of R25/kl (2013 base).
- On-grid electrical power is available from the local municipality at a cost of R1.00/kWh (2013 base), no maximum demand charge applies.

- On-grid electrical power cost will increase by 12% per year for the next five years; thereafter it will increase at the rate of inflation.
- Ferromanganese prices will rise in rand terms at the rate of inflation.
- Safety legislation is stringent and expected to tighten.
- Skilled labour is expensive and less available in future.
- Support systems are well developed and in close vicinity.
- The coal mine is 80 km from the plant.
- The ore mine is 640 km from the plant.
- The furnace has a reduction reaction surface area of 22 m^2.
- Fuel gas (natural gas from SASOL) is available at a cost of R3.00/kg (2013 base). The cost is expected to increase at the rate of inflation.
- Coal is available at a cost of R490/ton at the mine (2013 base).
- The plant will operate up to 2023.

Scenario 2: FCP is located next to the ore body

- The plant is located in Hotazel, South Africa.
- Water is a scarce resource; a new pipeline will have to be installed delaying project start-up and increasing water cost to R35/kl (2013 base).
- On-grid electrical power is available from ESCOM at an equivalent cost of 70c/kWh (2013 base) [84].
- On-grid electrical power cost will rise by 8% per year over the life of the plant.
- Water cost will rise by 10% per year over the life of the plant.
- Ferromanganese prices will rise in rand terms at the rate of inflation.
- Safety legislation is stringent and expected to tighten.
- Skilled labour is very expensive and scarce.
- The coal mine is 720 km from the plant.
- The ore source is next to the plant.
- The plant has a reduction reaction surface area of 220 m^2.
- Fuel gas is not available.
- Coal is available at a cost of R490/ton at the mine (2013 base).
- The plant enters operation in 2023 and operates for a minimum of twenty years.
- No external oxygen supply will be available.
- Funds are available to incorporate energy efficiency and opex reduction measures.
- Coal is transported to the plant by road.
- ECM technology will reduce in cost and improve in efficiency.

2.7.2 System context

Scenario 1 will be considered in this study as a background to determining the effect of the ECMs selected for implementation on LP1. In Chapter 6, Scenario 2 will be used as background to predict the potential efficiency and cost of FCP.

A context diagram for Letaba and future plants is shown in Figure 7.

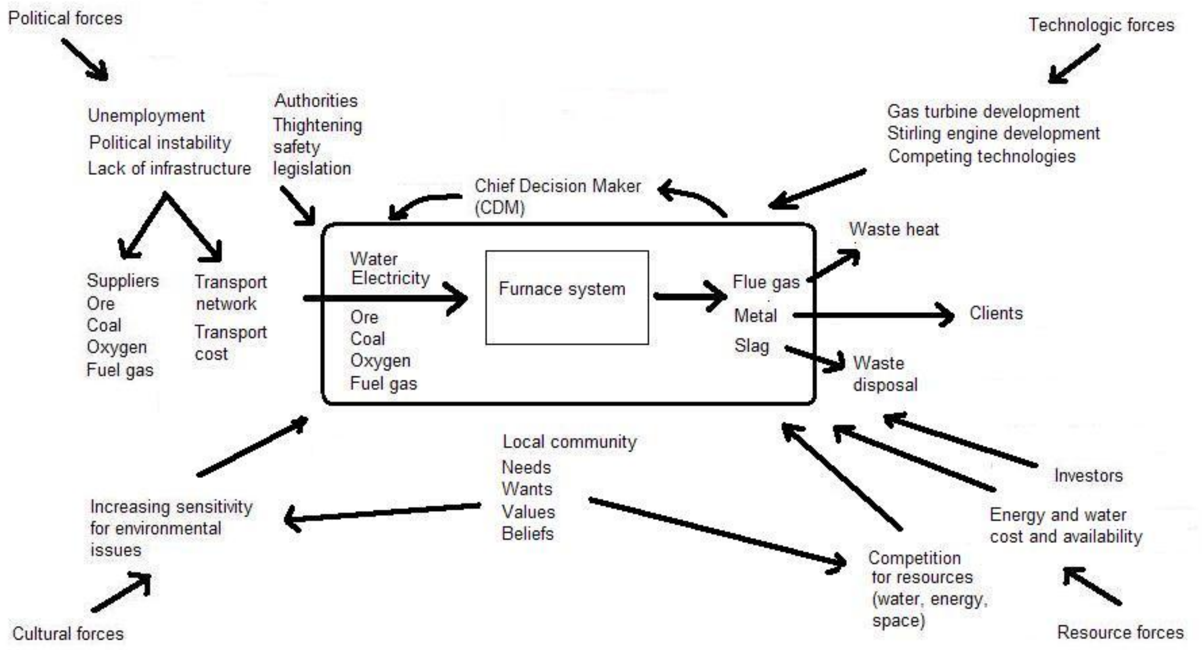

Figure 7: System context diagram

The boundary of the plant can be drawn in a number of ways. According to Athey the boundaries are determined by the authority of the chief decision maker, in this case the plant owner [77]. In this study the boundary is the physical boundary of the plant.

For Letaba fuel gas supply, oxygen and electrical generation to feed the grid fall outside the boundaries of the plant, so the generation of those three commodities are external to LP1 and LP2.

The sensitivity of key external interfaces is now briefly reviewed in order to identify potential opportunities and threats that could affect both Letaba and the first commercial plant.

Ore supplier:

The AlloyStream^{TM} technology has a beneficial effect on the ore supplier – waste ore can be sold, increasing revenue and profitability and reducing environmental footprint.

Coal supplier:

Coal suppliers will view the AlloyStream^{TM} technology as positive as it uses more coal than the alternative SAF process, neglecting coal burned in thermal power plants to supply the SAF-based process with electricity. Coal suppliers fetch a higher price for coal from AlloyStream than from the state-owned power utility.

Electricity supplier:

The electricity supplier should view an AlloyStream plant in a positive light since it means more business for the utility. Energy efficiency improvements - yielding a reduction in electricity use - could also be viewed as positive, and even more so if the plant can become a net producer of electricity that is fed into the supplier’s grid.

Oxygen, fuel gas and water suppliers:

All three suppliers should view Letaba in a positive light even though consumption may reduce, since the plant’s operational life could be extended. They will probably have a neutral position towards FCP.

Local community:

Letaba has generated more than 100 direct jobs; FCP will generate more than 150. Both plants will, however, impact negatively on the physical environment, even though AlloyStream will attempt to minimise the impact. FCP could also be in competition with the local community for scarce natural resources, such as energy and water, although industrial development often improves the availability of these resources. Solutions resulting in a reduction in electricity usage (and even possibly producing excess electricity) and a reduction in water consumption will be viewed as positive by the community.

Controlling authorities:

The controlling authorities should have a positive to neutral position with regards to FCP. Any reduction in consumption of natural resources will probably be viewed as positive, as will measures limiting the negative impact on the environment.

Slag user:

AlloyStream has successfully had its slag classified as a by-product. Slag produced by Letaba is used as a replacement for sand in the cement product manufacturing process. The local cement product industry should view an AlloyStream plant as positive since it improves their profitability.

Investors:

The potential solutions have both a negative (increased capex) and positive (reduced opex, faster start-up) impact on the return on investment. Investments are primarily determined by the bottom line: the payback period will probably be the dominant criterion applied when selecting feasible solutions. It is likely that the long-term benefits of improved energy efficiency will be welcomed by the investors.

2.7.3 Constraints

The constraints applicable to LP2 and FCP are:

- Payback period must be less than twenty years for ECMs to be considered as viable.
- The performance of the reduction process must not be negatively affected.
- Statutory requirements must be met.
- Oxygen must be internally generated for FCP.
- Only solutions that are commercially available at present may be incorporated into LP2.
- Solutions that may only be proven in ten years' time can be considered as options for FCP.

Ackoff, as does Athey, cautions against application of constraints early in the problem-solving process [85]. It is important to have visions of a better state, and this vision generating process can be hampered by one's own assumptions of what is possible, in other words self-imposed constraints. Ackoff promotes what he calls proactive planning – a process in which a future goal is created and ways devised to approach the goal as effective as possible. The author attempted to follow this ideal throughout this study.

Table 2 describes some elements of a desired future state and the related present state of the elements.

Table 2: Present and desired future state of important factors

Factor	Present state	Desired future state
Safety	The lost-time injury frequency rate (LTIFR) of LP1 is higher than the industry norm.	LTIFR must be lower than the industry norm.
Energy efficiency	The energy efficiency of LP1 is low.	The efficiency of LP2 should be at least 10% better than LP1. FCP should be at least 10% better than LP2.
Reliability (complexity)	LP1 has a reliability (expressed as availability) exceeding 95%.	LP2 availability should be equal or better than 95%.
Dependence on grid power	The existing plant is reliant on external power to operate productively. The effect of short duration outages are negated with emergency diesel generators.	Future plants should be off-grid capable.
Dependency on the availability of water	The existing plant is totally dependent on an external supply of water, except for short-term outages.	Future plants should use less water than LP1. A dry-cooling capability must be offered.
Financial (cost of electricity, oxygen, water, fuel gas and transport)	A substantial increase in the cost of all four utilities and transport is expected over the next five years. The current combined cost (2013 base) represents more than R5 000/ton metal.	A reduction in operating cost of more than 30% is required for LP2 and more than 50% for FCP compared to LP1.

2.8 Evaluation criteria and system utility function

2.8.1 Evaluation criteria

Four criteria were selected for the evaluation process:

- Broad social impact
- Operational reliability
- Financial performance (measured in payback years)
- Safety

These criteria are similar to the criteria proposed by Aflaki et al. [86]. Basic definitions of the criteria are:

- **Broad social impact** (abbreviated to "social" in this study) – this criterion incorporates the non-quantifiable value of the ECM as seen by parties in the immediate and general environment of the plant. Examples of parties are investors, local community, potential clients, non-governmental organisations, as well as governmental organisations focused on community development and environmental issues.
- **Operational reliability** – this criterion attempts to describe the non-financial impact on the plant due to the expected reliability of the ECMs that are considered for implementation. Billinton and Allen [87] define reliability as "the probability of a device performing its function as intended under the operating conditions encountered for the time period required". In this study device means the hardware related to the ECM. Operating conditions means the impact that other systems have on the ECM, including maintenance and operating practices. Time period is interpreted as the expected lifespan of the ECM hardware, typically twenty years.
- **Financial performance** – a simple payback model was used with payback period calculated as the cost of implementing the ECM divided by the savings per year (in most cases due to less energy use). It is assumed that where existing equipment is replaced the replaced equipment has no financial value.
- **Safety** - under this criterion only the risk posed to people employed at the plant as a result of ECM failure is considered, and only while operating the equipment. The risk during construction is not considered.

2.8.2 Ranking of criteria

The four criteria were ranked by Johan Groenewald (the AlloyStream general manager), the author and Johan Nel (an independent consultant with sound understanding of the industry). The individual ratings are shown in Table 3 in the sequence that the individuals are mentioned above. The ratings by the three individuals are close, indicating considerable agreement on the relative values of the criteria.

Table 3: Preference chart

Criteria	Financial	Safety	Reliability	Social	Total
Financial		3,3,3	3,1,2	0,1,0	6,5,5
Safety	1,1,1		1,1,2	0,1,0	2,3,3
Reliability	1,3,3	3,4,3		1,2,0	5,9,6
Social	4,4,3	4,4,4	3,4,4		11,12,11
Totals	6,8,7	10,11,10	11,6,11	1,4,0	(24,28), (29,29), (25,28)
Combined and normalised	6	8	5	1	
Sequence of questions: top to left, e.g. Is financial (top) more or less important than safety (left). All three evaluators scored a 1, meaning "less". Meaning of values: 0 - much less, 1 – less, 2 – equal, 3 – more, 4 – much more					

2.8.3 System utility function

The next step in the process is to develop a utility function for each criterion that defines poor to good performance. Five performance levels are used:

Barely acceptable	(score 1 or 2)
Below average	(score 3 or 4)
Average	(score 5 or 6)
Above average	(score 7 or 8)
Exceptional	(score 9 or 10)

The full utility function is attached as Appendix A. The method followed to determine the safety score is explained below.

The safety criterion models the probability of operating personnel being harmed by the system. It is the combined probability of system failure AND the probability that the failure will harm people in the immediate vicinity AND the probability that people are in the immediate vicinity of the system [88]. Performing a sound event probability calculation is beyond the scope of this study. A simple albeit subjective approach was followed. To arrive at a single score (1 to 10) each of the three factors was allocated a value from the system utility function for each ECM and the following calculation performed:

Equation 3: Simple probability calculation

Value = (factor1+factor2+factor3)/3.

A panel familiar with the plant did the scoring. The team consisted of the author, Stella Gleimius (a senior process engineer) and Murray Duigan (a senior mechanical engineer).

Each ECM was rated and scored against each of the four criteria; each score was qualified with a confidence rating. The confidence rating was allocated by the author. Only three confidence levels were used and these levels are defined as follows:

- **Low confidence (score 0.1)** - the author has no experience of the ECM and no independent publications could be found.
- **Medium confidence (score 0.5)** - the author has experience of the ECM, and/or independent publications not directly related to the ECM were found, and/or datasheets from potential suppliers were found and/or experienced persons agreed with the values.
- **High confidence (score 0.9) –** Similar or identical systems were studied by AlloyStream and/or implemented on Letaba and/or commercially valid quotations were received and/or directly applicable independent publications were found.

2.9 Conclusion

The development of the AlloyStream^{TM} technology has progressed to the present state where a prototype plant is in operation. As part of the product development program energy efficiency must be addressed, even if only on a conceptual level. Energy efficiency is a market requirement for any new smelter and even more so when the smelter is based on new process technology. Investors must be confident that the required efficiency will be met before funds for construction will be released.

In this chapter two scenarios were developed, one applicable to Letaba and the other applicable to FCP. Constraints that potential solutions will have to meet were identified and listed. A system utility function and four criteria that will be used to evaluate the feasible ECMs were developed and the relative importance of the criteria determined.

CHAPTER 3

In Chapter 3 twenty ECMs are defined. The energy conservation performance of each ECM is predicted and the ECM rated against the four criteria (as discussed in Chapter 2). A confidence rating is attached to the value rating of each ECM. The relative worth, or value, of each ECM is then determined. The calculations and reasoning that were followed to arrive at the predicted energy conservation achieved by each ECM are described.

When a man does not know what harbour he is making for, no wind is the right wind. ~Seneca

3 Design strategies for an energy efficient plant

3.1 Overview

Considering the information emanating from the literature survey it became clear that energy efficiency improvement can be achieved by the following strategies:

1. Improve the efficiency of converting electric power to shaft power, or heat in the case of the inductor.
2. Utilise solar radiation at the plant to generate electricity, and natural lighting to reduce the electrical load.
3. Improve the efficiency of mechanical devices driven by electric motors (such as gearboxes, conveyors, compressors and pumps).
4. Reduce the thermal energy leaving the furnace through the furnace walls.
5. Use waste heat to dry raw material, and/or heat to heat gases, and/or ore and coal, before it enters the furnace.
6. Use waste heat to drive a heat engine to generate electricity.
7. Use pressure energy from the oxygen entering the plant via pipeline to generate electricity.

It is also clear that a number of alternative measures could be considered under the same strategy; some would be mutually exclusive, hence the need for some structured selection process. By determining relative value the selection of the most promising measures can be made in a defendable manner.

In this chapter the various strategies are expanded to energy conservation measures and the performance of each ECM is predicted on a standalone basis.

3.2 Strategies and available technologies

Thermodynamics and heat transfer play a dominant role in pyrometallurgical plants. It is therefore prudent to briefly review the laws of thermodynamics and the applicable principles of heat transfer.

Thermodynamics primarily addresses the transformation of heat into other forms of energy and vice versa. Ever since man learned how to make and control fire he has been searching for ways to turn heat into work.

Heat transfer is a branch of engineering that studies the transfer of heat, which is invariably important to thermodynamics. Both branches of science are based on proven principles (or laws in the case of thermodynamics).

The first and second laws of thermodynamics are of particular interest to this study. The first law of thermodynamics dictates the conservation of energy (excluding nuclear reactions). For a system that converts heat into work, the heat entering the system equals the work produced by the system, plus the heat leaving the system. This is represented by the following equation:

Equation 4: First law of thermodynamics

$Q_{in} = W_{out} + Q_{out}$ [81,82]

Where:

- W_{out} is the work produced by the system
- Q_{out} is the heat leaving the system

The second law dictates that not all heat entering a thermodynamic cycle can be converted into work [81,82]. The best possible conversion efficiency is given by the following equation [81,82]:

Equation 5: Maximum second law cycle efficiency

$P = 1 – T_{0/}T_{max}$

Where:

- T_0 is the ambient temperature
- T_{max} is the maximum temperature of the Carnot Cycle

Although the zeroth and third law of thermodynamics are background to this study, a humorous and quite revealing interpretation of the first, second and third laws of thermodynamics, called Gingsberg’s theorem [89], with an analogous formulation of the zeroth law states:

• Zeroth law:	You have to play the game
• First law:	You cannot win
• Second law:	You cannot break even
• Third law:	You cannot even get out the game

Exergy, or thermodynamic availability, is the maximum work that can be done by a thermodynamic system. In other words, exergy is work done by a system or the ability of the system to do work. Mathematically [10]:

Equation 6: Thermodynamic system's work produced by a reversible process from state 1 to state 2

Exergy (E_x) $= U_1 - U_2 - T_0 (S_1 - S_2)$ [10]

Where:

- U the internal energy
- T_0 is the heat sink temperature (or temperature of the environment or ambient temperature)
- S is the entropy at states 1 and 2

The exergy of materials is calculated in a similar manner for a substance, except that the environmental state of the species forming the substance is considered [10].

Kern defines heat transfer as "the science which deals with the rates of exchange of heat between hot and cold bodies". Heat can be transferred from a hot body to a cold body by four mechanisms: conduction, convection, radiation and diffusion [90].

The implication of these principles for this study is three-fold – not all the heat generated by Letaba can be recovered (otherwise no heat transfer can occur) and only a portion of the heat recovered can be turned into work (or electricity) according to the second law of thermodynamics.

Two main types of energy enter the plant: electrical and chemical. The plant uses the energy to:

- Enable the reduction process.
- Transport materials such as ore, metal and slag.
- Transport fluids (gases and water).
- Maintain the conditions necessary for the plant to operate (cool the furnace shell and the inductor coil, provide sufficient lighting and ventilation et cetera).

In this study the plant is viewed as a thermodynamic system that turns input energy into useful work and rejects waste heat. The purpose of the plant is to produce metal from ore. The theoretical energy required for this reaction is the reduction work or exergy. The energy efficiency of the plant is defined as the ratio of exergy to energy entering the plant, or product exergy to input energy. The first law of thermodynamic dictates that the energy entering the plant equals the energy leaving the plant. The second law of thermodynamic dictates that the exergy entering the plant must be more than the exergy leaving the plant.

The product from the plant was defined as metal; the exergy of the metal was not calculated. To overcome the lack of information a pragmatic approach is followed and the metal enthalpy calculated by Tangstad and Olsen for a typical ore used as an estimate of the product exergy [1].

Various ECMs can be considered to improve the energy efficiency of LP1. These are:

1. Improve the efficiency of converting electric power to shaft power, or heat in the case of the inductor.
    - High-efficiency motors and drives: improving the conversion efficiency of electrical-to-mechanical power in the case of electrical motors is commercially viable and was introduced during the construction of the Letaba plant to a limited degree.

      ECM1: *Replacing all the remaining motors with high-efficiency units.*

    - Inductor efficiency: the inductor installed on the Letaba furnace was reused from the previous Rivet plant and has an efficiency of 66%. Current designs offer efficiencies of 71%.

      ECM2: *Replacing the unit with a higher efficiency unit.*

2. Intensify natural lighting: when Rivet was upgraded to Letaba the existing high-efficiency lighting was retained. Augmenting these with light pipes, or light tubes, during daylight hours will reduce the electricity use.

    ECM3: *Installing light tubes.*

3. Utilise solar radiation to generate electricity:
    - The Letaba plant area is approximately 10 000 m^2, with 4 000 m^2 under roof. Two commercial solar-to-electricity technologies exist: PV (solar energy is converted directly into electricity), and solar thermal (a fluid is heated in solar collectors, and the collected heat is then used by a heat engine such as Stirling, Rankine or Organic Rankine to produce electricity).
    - Both technologies are proven, but only PV will be considered for LP2.

ECM4: *Using solar-to-electricity technologies.*

4. Improve the efficiency of mechanical devices driven by electricity, such as gearboxes, fans, conveyors, compressors, pumps and so forth:
    - The selection of existing devices was only based on cost and availability, so some room for improvement in energy efficiency is possible.

    ECM5: *Improving mechanical efficiency.*

    Note:
    One measure was implemented with the upgrade from Rivet to Letaba – improving the water-cooling circuit resulted in a significant reduction in specific pump power. Since it was already present when Letaba was built it is considered part of the LP1 configuration and is therefore not discussed in this chapter. After the first campaign a second measure was implemented – installing a low-pressure blast air system, as discussed in Section 3.3 as ECM5b. Both the improved water-cooling system and the low-pressure blast air system will be reviewed in Chapter 5.

5. Reduce the thermal energy leaving the furnace through the furnace walls:
    - The heat loss through the furnace walls is substantial. About 30% of the inductor output and 40% of the combustion heat output exit the furnace through the refractory lining. Apart from the roof, no significant reduction of heat loss can be achieved by modifying the refractory, leaving the option of increasing the shell temperature to reduce the ΔT across the refractory.

    ECM6: *Redesigning the roof refractory.*
    ECM7: *Increasing the shell (and roof) temperature.*

6. Use waste heat to heat ore and coal before it enters the furnace and/or to heat blast gases, and/or to dry raw material:
    - So-called preheating of raw material with waste heat is a potential solution that is applied with some success in other pyrometallurgical processes.

    ECM8: *Preheating raw material.*

- Preheating of combustion gas is a standard solution in especially glass furnaces.

  ECM9: *Preheating of combustion gas.*

- Drying feed material was identified by a number of sources. Coal drying with waste heat will be considered for LP2.

  ECM10: *Drying coal with waste heat.*

7. Use waste heat to drive a heat engine to generate electricity:
    - Recovering waste heat and converting some of the thermal energy to electricity is a potential solution applied in various industries. This is unquestionably a potential solution, but the question is which thermodynamic cycle to apply. In this regard six cycles were considered: SC, BC, SRC, ORC, KRC and a combined Brayton-ORC cycle.

      ECM11: *Converting off-gas waste heat to electricity.*
      ECM12: *Converting metal and slag waste heat to electricity.*
      ECM13: *Converting waste heat from the cooling circuits of the furnace to electricity.*

8. Use pressure energy from the oxygen entering the plant to generate electricity or replace electrical drives:
    - Recovery of pressure energy from gas streams is applied in the oil and gas industry by turbo-expanders and turbo-generators.

      ECM14: *Recovering pressure energy from gas streams.*

The ECMs identified all meet the constraint of being internal to Letaba. Being self-sufficient (where oxygen and electricity generation are concerned) could be a requirement for future deployment of the AlloyStream^{TM} technology; this is briefly discussed in Chapter 6.

3.3 ECM performance simulation

The performance simulation of the ECMs considered is based on the assumption that they are implemented one at a time on LP1, and that only a single ECM is implemented at any time.

3.3.1 ECM1 – Replace existing IE1 motors with high-efficiency IE3 motors

The motor failure probability is very low and should a failure occur the risk to people would be very low. There are seldom people in close proximity to the motors. Only three of the existing motors are high-efficiency or IE3 standard. An estimated 700 kW motor power is IE1 rated. Replacing the IE1-rated units with IE3-rated units will reduce electricity use by at least 3% [91], resulting in a total expected reduction in electricity use of 21 kW. At 100c/kWh and a replacement cost of R1 040/kW [92] the payback period is between four and five years at 8 500 operating hours per year. The replaced motors will be kept as spares. The payback period correlates closely with Chen et al. [19], who found it to be 4.7 years. No change in reliability is expected. The social value is deemed insignificant.

- Safety score = 10, very confident.
- Financial score = 7, very confident.
- Reliability score = 9, very confident.
- Social score = 4, confident.

3.3.2 ECM2 – Upgrade the inductor to a high-efficiency configuration

Upgrading the inductor should not change the risk profile of the existing unit. As is the case with ECM1, this ECM does not add additional hardware. The failure probability of the modification is low (the upgrade is a standard for all new ABP inductors). Should the inductor fail it is likely that people in its vicinity will be harmed, but no-one is allowed close to the unit. A 5% reduction in electricity use of the coil is predicted by the inductor system supplier ABP. The power loss in the coil before upgrading is 853 kW; after the upgrade it reduces to 804 kW; a reduction of 49 kW in electrical power use. At 100c/kWh and a capex cost of R5 000 000 (budget price from the supplier), the payback period is five to six years. The inductor reliability should not change because of the upgrade. The improvement of the inductor efficiency will be welcomed by the project sponsor.

- Safety score = 8, very confident.
- Financial score = 6, very confident.
- Reliability score = 5, very confident.
- Social score = 5, confident.

3.3.3 ECM3 – Augment existing lights with light tubes during daytime

The Environmental Regulations for Workplaces of the Occupational Health and Safety Act (Act 85 of 1993) specifies a minimum luminance for foundries (charging floor, tumbling, cleaning etc.) of 100 lux. The luminance of sunlight at peak is close to 100 000 lux/m² and on average over an 8 hour period is about 40 000 lux/m². Using the average luminance 1 m² of light tube can illuminate 400 m². However, to compensate for inefficiencies and lower light levels early and late in the day a ratio of 1:200 will be used. The ratio compares with the recommended ratio of 1:200 from SunbirdSkylights [93]. This means that the roof area covered by light tubes will only be 0.5% and will therefore have an insignificant effect on ECM4. Solar light tubes will have a low failure rate with minor effect on people in the vicinity. There are sometimes people in the vicinity of the tubes. The cost is R85/m^2 for the light tubes plus an estimated R30/m^2 for the installation [93]. The total capex is R460 000 for an area of 4 000 m^2. An electricity use reduction of 20% for the existing lights is predicted. Based on the existing lighting electrical load of 50kW at 100c/kWh the payback period is five to six years. The system should be very reliable. Due to the high visual impact and low technology level the social value is deemed high.

- Safety score = 7, very confident.
- Financial score = 7, very confident.
- Reliability score = 9, very confident.
- Social score = 7, very confident.

3.3.4 ECM4 – Use PV solar to generate electricity

It is highly unlikely that the system will fail in such a way that it can harm people in the immediate vicinity. It is also unlikely that anyone will be in the immediate vicinity. The cost of commercially available mono-crystalline cells is about R25/W with conversion efficiency in optimum conditions of 17%. This was confirmed with a local supplier [49]. This conversion efficiency will not be achieved due to the orientation of the roof, losses in the wiring and losses in the inverters. An overall efficiency of 8% will instead be used.

The capex cost, including installation, is estimated at R4 000/m^2 including storage batteries and inverters, or about R3 000/m^2 excluding batteries. Almost the full roof area of 4 000 m^2 can be used. At 5 kWh/(m^2.day) solar radiation [11] and 8% effective overall conversion efficiency (solar radiation to power) 1 600 kWh per day of electrical power can be generated. The expected lifespan of the panels is more than ten years. The payback period (excluding maintenance) is twenty to twenty-one years for a system with no batteries. This payback period does not meet the constraint imposed on ECMs to be twenty years or less. However, the social value of the ECM is so significant that the constraint will be waived for this ECM.

Although regular cleaning will be required the ECM should be very reliable, and the social value very high.

- Safety score = 9, very confident.
- Financial score = 1, very confident.
- Reliability score = 8, confident.
- Social score = 9, confident.

3.3.5 ECM5 – Improved mechanical device efficiency

The ranking of electricity use by mechanical devices (all driven by electrical motors) are:

• Compressors	364 kW	Fixed speed direct online (DOL) motors
• Water pumps	150 kW	Fixed speed DOL motors
• Induced draft fan	75 kW	Driven through VSD, fitted with VVID
• Crushing plant	15 kW	Fixed speed DOL motors
• Conveyors	30 kW	Fixed speed DOL motors
• Various other small loads	40 kW	Mostly driven through VSDs

3.3.6 ECM5a – Install VSDs on all drives above 3 kW

The average power draw of devices not fitted with VSDs is 559 kW. The compressor power and the crusher will not be considered as part of this ECM, as the low-pressure blast system (ECM5b) replaced the compressors and the crusher is either run on full power, idled or stopped. The remaining drives will be fitted with VSDs to achieve a predicted power reduction of 5% due to more accurate load matching. The cost of VSDs is approximately R600/kW based on a budget price from WEG [92]. The payback period will be one to two years. In comparison Chen et al. found the payback period to be 0.3 years [19]. Fitting VSDs to motor drives will not affect safety adversely, nor should it reduce reliability. The social value is deemed insignificant.

- Safety score = 10, very confident.
- Financial score = 9, very confident.
- Reliability score = 7, confident.
- Social score = 4, confident.

3.3.7 ECM5b – Use low-pressure blast air

Improvements could be possible by redesigning the mechanical devices or systems driven by the electric motors; the most significant of these was done as part of this study when a low-pressure blower system was installed to replace the blast air system supplied by the compressors. Another significant improvement in this category was the redesign of the water-cooling system to a high-ΔT design. The water plant redesign is already incorporated in LP1. It is therefore not included as an ECM to upgrade LP1 to LP2. The low-pressure blast air and redesigned water-cooling systems are discussed in Chapter 5. The low-pressure blast air system will form ECM5b.

ECM5b replaced two screw compressors and a high-pressure air measurement, control and distribution system with twelve individual blowers. System pressure dropped from 7.5 bar to 3 kPa. It is very unlikely that the blowers will fail in such a way that they could cause harm to someone in the vicinity. They are placed in an area that is occasionally visited by plant personnel.

The blowers, VSDs, additional hoses and measuring systems cost R1 500 000 (capex). It reduced the electricity use from 364 kW to 48 kW, an opex reduction of R316/hour. The payback period is less than one year. The new system’s reliability should be at least as good as the system it replaced. The social value is deemed significant.

- Safety score = 8, very confident.
- Financial score = 9, very confident.
- Reliability score = 7, confident.
- Social score = 6, very confident.

3.3.8 ECM6 – Reduce heat loss by upgrading the furnace roof refractory

The LP1 furnace roof is lined with an in situ cast refractory with a thickness of 150 mm. The WA350 mild steel panels are water-cooled at 40°C. In the glass industry it is common practice to use brick-type refractory for the gas furnace roofs instead of refractory casting (as is the case with LP1). This will require a redesign of the roof panels and feed ports as the brick refractory is 450 mm thick and will increase the existing refractory mass by a factor of 3. The new refractory configuration will result in heat loss reducing from 1 000 kJ/s to 350 kJ/s for the same ΔT across the lining. The new refractory mass is estimated at 27 ton.

At a cost of R15 000/ton the capex for the new refractory will be R405 000. The new steel roof will have a mass of about 15 ton at R40 000/ton; resulting in a cost of R600 000. Eight new feed ports will cost R50 000 each. The cost estimates are taken from the 2012 Rivet to LP1 upgrade. The total estimated capex is R1 405 000. A reduction in fuel gas use of 16g/s (56 kg/hour) is predicted, yielding an opex reduction of R168/hour. The payback period is less than a year. No significant change in the safety risk is foreseen. The reliability should be better than the existing design. The social value is deemed insignificant.

- Safety score = 7, very confident.
- Financial score = 9, very confident.
- Reliability score = 5, very confident.
- Social score = 5, confident.

3.3.9 ECM7 – Reduce heat loss through the furnace walls and roof by increasing the cooling fluid temperature

The existing shell is cooled over 80% of its area with water that is circulated through water channels under 6 bar pressure; the balance being cooled with forced and natural air movement. In addition, the slag line is cooled with water-cooled copper blocks situated inside the refractory lining. The roof is fully water-cooled. The water temperature circulating through the cooling circuits is maintained between 40°C and 50°C. The water-cooling system, and especially the copper coolers, ensures a very high rate of heat removal relative to the heat transfer from the gas, slag or liquid metal to the refractory hot face. This promotes a self-healing mechanism (called a “freeze lining”) that ensures extended refractory life.

Although the forming and maintaining of freeze linings is not an exact science, it is known that a high heat transfer rate from the heat source to the cooling medium causes the hot surface temperature of the refractory in contact with for example, liquid slag, to drop below the solidification temperature of the liquid. By properly selecting the refractory and cooling of the cold side of the refractory the liquid will solidify against the refractory hot face and protect the refractory from thermal accelerated abrasive wear and chemical deterioration.

Accelerated wear was experienced firsthand with Rivet campaigns 1 to 3. In preparation for Rivet campaign 4 copper-cooling blocks were introduced in the slag-line area and at the taphole, resulting in a significant reduction in wear. For Letaba the design was extended to two rows of coolers, yielding even better results.

The temperature of the cold face is not as important as the ability of the cooling system to maintain the temperature at very high heat fluxes. In theory the existing practice of circulating water at about 40°C at a pressure of about 6 bar can be replaced with water at a much higher pressure and temperature, for example 20 bar absolute and 180°C, 32°C below the boiling point at 20 bar absolute.

This approach, however, poses a significant risk. If a circuit fails at 20 bar pressure and temperature of 180°C, the water will flash boil resulting in a mixture of steam and boiling water being released at high velocity - a lethal combination to anyone in the vicinity of the failure. High-pressure circuits will also require a complete redesign of the existing components, thus increasing capital cost. Water treatment is also affected – at temperatures above 60°C the water quality becomes critical as dissolved salts, mainly calcium carbonate, tend to precipitate out and deposit on the metal surfaces, thereby reducing the heat transfer coefficient [94].

An alternative to high-pressure water is thermal oil. Typical applications are in ORC systems where an oil temperature of 300°C and oil pressures of 2 to 3 bar are common. [95]. Thermal oil also poses significant risk, but less so than high-pressure hot water. The oil pressure is low and no flash boiling will occur in the event of the release of fluid. Thermal oil, however, has an additional risk – it will ignite if comes into contact with oxygen and a high temperature ignition source such as someone welding in the vicinity of a leak. Only the thermal oil system will be considered in this study.

The physical characteristics of thermal oil differ from water (the existing cooling fluid) in the following significant ways:

1. The oil viscosity at 316°C is 0.462 cP [93], slightly less than the water viscosity of 0.547 cP at 50°C. Therefore, the Reynolds number, and as a result the pressure drop for the same wetted perimeter and flow rate, will be very close to that of water.
2. The specific heat of oil is about 2.8 kJ/kg.K, or 67% that of water [93], so for the same heat transport rate (kJ/kg.s) the mass flow of oil will have to be 30% more than that of water; or the ΔT will have to be 30% more than that of water.
3. The upper working temperature limit of thermal oil is about 350°C [93]; with water the upper limit is pressure-dependent. For example, large power station boilers operate at pressures of about 200 bar At that pressure the boiling temperature is 366°C.

An average oil temperature of 300°C will be used for the evaluation (typically 280°C into the circuits and 320°C out). An inductor-cooling circuit has not been considered due to the critical nature of the inductor coil and refractory.

Given the above, it is safe to assume that for ECM7 the existing water-cooled components will not have to be replaced. The total capex therefore includes the cost of new piping, new pumps, an oil reservoir, oil, and an oil-to-air heat exchanger (or heat exchangers). This is estimated as R5 000 000. The opex saving will include less fuel gas use, less electricity use by the inductor, water pumps and cooling towers and less water evaporation.

Since the ΔT across the refractory will change from 1 500°C for water-cooling to 1 250°C for thermal oil-cooling, the heat loss through the furnace walls will be reduced by 18%. This translates to a reduction in heat loss of 872 kJ/s, of which 30 kJ/s is from the coolers that are in contact with the liquid metal. Therefore, a reduction in inductor input power of 30 kW can be expected. The calculated reduction in fuel gas consumption is 21kg/hour or R63/hour.

The oil circulation pump and heat exchanger fan power draw are assumed to be the same as the power reduction on the water pumps and cooling tower fans. Water evaporation should reduce by 0.8 kl/hour or R20/hour. The total opex reduction is R128/hour, giving a payback period of four to five years. The thermal oil system will increase the safety risk. From a social point of view oil spills would have a negative implication whilst the reduction in water consumption will be positive. The social value is deemed low.

- Safety score = 4, confident.
- Financial score = 7, very confident.
- Reliability score = 5, very confident.
- Social score = 3, confident.

3.3.10 ECM8 – Preheat raw materials

Preheating of raw materials could have benefits [23], however, for Letaba there are significant constraints. Since the raw material is a mix of ore and coal, the raw material cannot be preheated to more than 400°C - the point where the coal will start to devolatilise. It is also difficult to transfer heat reliably to the solid mix. For example: a raw material preheating system was installed in a titanium oxide smelter in 2002, but the system was never put into operation successfully (confirmed by the author during personal discussions with the plant manager). This option is deemed potentially unreliable and could pose substantial safety risks.

The solution will entail a major change to the furnace building design (to gain height), an additional conveyor and eight heat exchangers at an estimated additional cost of R10 000 000. Preheating to 250 °C reduces the oxygen use by 10% giving a cost reduction of R67/hour. The payback period is seventeen to eighteen years. The heating will be done with thermal oil from ECM7. The social value is deemed insignificant.

- Safety score = 5, confident.
- Financial score = 2, low confidence.
- Reliability score = 3, confident.
- Social score = 4, confident.

3.3.11 ECM9 – Preheat blast air

Fuel gas, pure oxygen and air are injected into the furnace combustion chamber through twelve injection ports via stainless steel lances. Eight lances are supplied with air and oxygen with the remaining four supplied with fuel gas and air. A typical overall mass flow ratio is 1:2:6 (fuel gas: oxygen: air). Heating of oxygen is ruled out for safety reasons, as is heating of fuel gas to prevent cracking of the hydrocarbons. A 250°C air temperature limit was applied due to practical constraints imposed by the configuration of the furnace, and to suit the operating temperature of the thermal oil. The benefit of preheating is a reduction in either the fuel gas flow or the oxygen flow – only oxygen reduction is considered. To preheat the blast air will require twelve heat exchangers, an increase in flow resistance resulting in an increase in blast air power and stainless steel piping. It is assumed that hot oil is available from ECM7.

Based on a preheat temperature of 250°C, a 15% reduction in oxygen use or 149 kg/hour is predicted [9], resulting in a saving of R104/hour. The estimated capex is R3 000 000, giving a payback period of three to four years. The safety risk will be similar to ECM7. The social value is deemed significant.

- Safety score = 4, confident.
- Financial score = 7, confident.
- Reliability score = 7, confident.
- Social score = 6, confident.

3.3.12 ECM10 – Use waste heat to dry coal

Coal drying has to be done continuously to reduce the water content of the coal from 12% to below 4%.This is done to enable flow through the batching system and to reduce the negative effect due to evaporation of the water in the furnace. During the drying process the maximum coal temperature is limited to 100°C to reduce the risk of spontaneous combustion. In LP1 coal drying is done in a shell and tube heat exchanger with heat supplied by combusting fuel gas.

Sufficient thermal energy (196 kJ/s) is available in the off-gas leaving the stack to dry the coal. An off-gas-to-oil heat exchanger, pump, piping, thermal oil tank and oil-to-coal heat exchanger will be required at an estimated capex of R3 000 000. The reduction in fuel gas use is estimated at R54/hour. The estimated electrical load of the circulation pump is 5 kW. The payback period will be six to seven years. The use of hot oil introduces risks similar to ECM7. The social value is deemed insignificant.

- Safety: score = 4, confident.
- Financial: score = 6, confident.
- Reliability: score = 7, confident.
- Social: score = 4, confident.

3.3.13 ECM11 – Use off-gas waste heat to generate electricity

From an engineering point of view there are two challenges:

- How to transfer as much as possible of the off-gas thermal energy to the working fluid of the heat engine.
- How to achieve the best heat-to-power conversion by the engine.

Before each potential solution is discussed it is necessary to note some challenges and limitations applicable to all potential solutions discussed under ECM11.

Off-gas characteristics:

Apart from the mass flow and temperature the dust load in the off-gas is significant. LP1 experienced a dust load of 92 kg/hour during campaign 1. Invariably a heat exchanger will be used to transfer the thermal energy from the dust-laden off-gas to the engine's working fluid; this heat exchanger must function efficiently and reliably. Dust is "sticky" in the 1 550°C to 1 200°C temperature range as it is still in partial molten state. This rapidly clogs heat exchanger surfaces and is difficult to remove.

There are a number of possible ways to overcome the problem [35]. One option is to reduce the off-gas temperature by injecting air at the point where the gas exits the furnace; another option is to employ mechanical scrapers to clean the heat exchanger tubes. For safety reasons some air injection is required to combust any CO or H_2 that may enter the off-gas system. This dilution air reduces the thermal energy availability (reduces the temperature of the gas entering the heat exchanger), and thus the potential conversion efficiency, as well as reducing the temperature difference needed for high heat transfer rates. Dilution air also increases the thermal energy leaving the heat exchanger.

Heat transfer fluids:

The SC, KRC and ORC engines use thermal oil to collect heat from the heat source and transport the heat to the engine where the heat is transferred to the engine's working fluid. With the SRC and BC engines there is no intermediate fluid. The use of a heat transfer fluid can introduce additional heat transfer losses.

Maximum and minimum temperatures:

The maximum temperature that the heat exchanger can be subjected to is limited by material considerations. This limit is set at 1 300°C off-gas temperature, which is the upper limit of a Kanthal APMT tube [75]. A minimum off-gas temperature of 250°C sets the lower temperature boundary. This minimum temperature is needed to prevent condensation of corrosive gases and steam before or in the bag-house. This is to prevent bag blinding and corrosion of the bag-house structure. If thermal oil is used a maximum oil temperature of 350°C must not be exceeded to prevent oil degradation.

Heat transfer:

The KRC, ORC and SRC receive heat energy through boiling of a liquid at almost constant temperature. Thermal energy of the off-gas below the boiling temperature, plus the temperature difference required to transfer the heat from the gas to the boiling liquid, cannot be utilised. In the case of the BC engine heat is transferred to the working fluid (air) at constant pressure. It is thus theoretically possible to achieve an almost constant temperature difference between the off-gas and air as heat is transferred to the BC engine.

The overall heat transfer coefficient of the off-gas heat to the engine affects the heat transfer rate. This coefficient is determined by the coefficients of:

- The off-gas-to-thermal oil and thermal oil-to-working fluid for the SC, KRC and ORC
- The off-gas-to-air for the BC
- The off-gas-to-boiling water and steam for the SRC

The minimum (or pinch) temperature difference is set at 80°C for the SC, KRC, ORC and SRC. The minimum (or pinch) temperature difference is set at 160°C for the BC.

A high heat exchanger surface area will result in lower temperature differences and increase the thermal energy that can be recovered from the off-gas, but will increase the heat exchanger cost. Less surface area will have the opposite effect.

Heat rejection from the heat engines:

KRC, ORC, SRC and SC are “closed”, meaning the working fluid does not leave the engine. In the KRC, ORC and SRC the working fluid is expanded through a turbine, then condensed in a heat exchanger and pumped back to the boiler. To achieve a high thermal efficiency the working fluid must be condensed at the lowest possible temperature; usually attained by evaporating water in cooling towers. In the SC the working fluid must similarly reject heat to the sink at the lowest possible temperature. The BC rejects heat to the environment at a much higher than ambient temperature by discharging the working fluid (air) continuously to the environment – no cooling water is required.

Energy available:

The off-gas mass flow is 1.73 kg/s, c_p = 1.38; gas temperature leaving the furnace is 1 550°C; ambient dry bulb temperature is 21°C; thus giving 3 640 kJ/s sensible heat leaving the furnace. The maximum thermal energy available to a heat recovery engine is: $\dot{m}$ x c_p.(1550-250) = 3 104 kJ/s minus the thermal energy that cannot be utilised due to the pinch temperature.

3.3.13.1 ECM11a – Stirling Cycle

The only SC engine considered is the low-temperature unit under development by Cool Energy Inc. [97]. The unit receives heat at a maximum of 300°C and rejects heat to a cooling water circuit at about 21°C – values very similar to the ORC offered by Turboden.

Engines based on the SC have their origin in the early 1800s. The theoretical cycle has the same efficiency as the Carnot Cycle. Stirling engines can yield thermal efficiencies of more than 40% at a hot-end temperature of 760°C [98] and 25% at 300°C with a cold-end temperature of 20°C [97]. The engine transfers heat internally between a hot and cold surface with a gas (air, nitrogen or helium) as a working fluid. This results in the engine having a low specific power output, in other words it has to be large to produce significant power.

Based on a thermal oil temperature of 300°C and a pinch temperature of 80°C, thermal energy can be transferred to the SC from the off-gas at a rate of 2 793 kJ/s. With a cycle thermal efficiency of 24% a gross 670 kW will be generated. The net electrical output, however, is 670 kW minus oil, water pumps and cooling tower power (estimated at 100 kW) and a 2% loss in the inverter required to convert the direct current output of the engine to alternating current. The resultant power is 557 kW resulting in a reduction in grid electricity cost of R557/hour. The capex is estimated at R50 000/kW for the engine once in mass production (information from a personal discussion with the general manager of Cool Energy).

Other component costs are R600/kW for the inverter, R500/kW for controls, R3 000/(kJ/s) for the off-gas-to-oil heat exchanger, bypass ducting and dampers, oil tank, oil piping and pumps. The existing cooling towers, cooling water tanks and pumps will be used; the total capex is estimated as R36 841 000. Based on the electricity generation income of R557/hour minus a water use cost of R101/hour the payback period will be nine to ten years.

The thermal oil circuit will increase the safety risk. The system is complex, but the existing heat rejection system will be retained as a back-up. The ECM is deemed to have significant social value.

- Safety score = 6, very confident.
- Financial score = 4, low confidence.
- Reliability score = 7, confident.
- Social score = 6, confident.

3.3.13.2 ECM11b – Externally fired Brayton Cycle

The BC compresses air in a compressor, heats the air in a heat exchanger in the externally fired heat configuration, expands the hot air through an expansion device, then exhausts the air to atmosphere. As such the BC does not require an intermediate heat transfer fluid or cold-end heat exchanger with the resultant water loss. Externally heated (or fired) gas turbines (EFGT) are not freely available.

Commercially available gas turbines that can be converted to external heating have low compression ratios; as a result they have low thermal efficiencies compared to the internally heated (with liquid or gas fuel) high-pressure turbines. Flexenergy’s MT250 turbine has a thermal efficiency of 20% at full power with an estimated turbine inlet temperature of 950°C without recuperation (as would be the case for external heating) and 29% at air inlet temperature of 20°C with recuperation [99]. The compressor outlet temperature is 236°C for a compressor efficiency of 80%. With a minimum temperature difference of 160°C between the off-gas and the compressed air 2 755 kJ/s can be transferred to the turbine. A thermal efficiency of 20% yields a power output of 551 kW.

The cost of the turbine is R16 000/kW (budget price estimate from Flexenergy), the cost of the heat exchanger is estimated at R5 000/(kJ/s) and R500/kW is estimated for piping. Total capex is estimated at R25 622 000 with an electricity cost reduction of R551/hour giving a payback period of six to seven years. Stationary gas turbines are very reliable, requiring a major service every 100 000 hours [99]. The social value is deemed significant.

- Safety score = 8, very confident.
- Financial score = 6, confident.
- Reliability score = 7, confident.
- Social score = 6, confident.

3.3.13.3 ECM11c – Steam-based Rankine Cycle

Typical commercial plants run at 60 bar absolute steam pressure with 170°C superheat [100]. A thermal efficiency of 18% can be expected. The boiling temperature at 60 bar absolute is 280°C [101]. With a pinch temperature of 80°C, 2 841 kJ/s of thermal energy can enter the cycle, giving a gross power output of 510 kW. Pumping and cooling plant power is estimated at 90 kW, giving a net electrical power output of 420 kW.

The cost of the turbine is R5 000/kW [100], the cost of the heat exchanger is R3 000/(kJ/s), and the cost of piping and control is R500/kW. The total capex is estimated at R12 896 000. The water cost is calculated as R99/hour. The payback period is three to four years. The reliability of a steam system is expected to be lower than an ORC. The social value is deemed significant.

- Safety score = 7, very confident.
- Financial score = 7, confident.
- Reliability score = 6, confident.
- Social score = 6, confident.

3.3.13.4 ECM11d – Organic Rankine Cycle

Typical commercial plants run at 20 bar pressure with no superheat [32]. A thermal efficiency of 20% can be achieved at a boiling temperature of 250°C [96]. With a pinch temperature of 80°C, 2 912 kJ/s of off-gas heat can enter the cycle, giving a power output of 582 kW. Pumping and cooling tower power is estimated at 99 kW, giving an electrical power output of 492 kW.

The cost of the ORC is R30 000/kW [102], the cost of the heat exchanger and thermal oil circuit is R3 000/(kJ/s), and the cost of piping and control is R500/kW. Total capex is estimated at R23 700 000. This correlated with the budget price from Vuselela Energy, obtained in 2010 [103]. The cost of cooling water used is R99/hour. The payback period is five to seven years. The social value will be significant.

- Safety: score = 8, very confident.
- Financial score = 6, very confident.
- Reliability score = 7, very confident.
- Social score = 6, confident.

3.3.13.5 ECM11e – Kalina Rankine Cycle

A thermal efficiency slightly better than ORC can be achieved by the KRC, so an efficiency of 22% will be used to calculate the electrical output. More heat can enter the system due to the different boiling points of the dual working fluid [104, 31]. It is estimated that 3% more heat will enter the cycle than with the ORC, or 3 000 kJ/s, giving a gross power output of 660 kW. Pumping and cooling tower power is estimated at 100 kW. The net electrical power output will be 560 kW.

The cost of the system is expected to be more than the ORC due to the number of heat exchangers and the lower market penetration of the KRC. Capex is estimated at R34 500/kW which is 15% more than the ORC. The cost of cooling water used is R99/hour. A thermal oil circuit and heat exchanger will be required (similar to ECM11a, ECM11c and ECM11d). The cost estimate for the oil circuit, heat exchanger and controls is R3 500/(kJ/s). The total estimated capex is R28 600 000 and the reduction in electricity cost is R560/hour. The payback period is six to seven years. The social value is deemed significant.

- Safety score = 8, very confident.
- Financial score = 5, very confident.
- Reliability score = 7, very confident.
- Social score = 6, confident.

3.3.13.6 ECM11f – EFGT-ORC combined cycle

In this option an ORC receives the waste heat from the EFGT at 80°C less than the exhaust gas exit temperature from the EFGT. The ORC boiling temperature is set at 180°C with a thermal efficiency of 15% [38]. A total of 2 204 kJ/s exists the EFGT at 588°C of which 1 229 kJ/s enters the ORC. The ORC generates 144 kW. The combined power output is 695 kW.

Pumping and cooling tower power is estimated at 60 kW, giving an electrical power output of 635 kW and a water cost of R54/hour. Capex is R35 400 000 (from ECM11b and ECM11d). The payback period is six to seven years. The social value is deemed significant.

- Safety score = 7, very confident.
- Financial score = 6, confident.
- Reliability score = 6, confident.
- Social score = 6, confident.

3.3.14 ECM12 – Use waste heat to electricity from metal and slag

Two ton metal and two ton slag are tapped from the LP1 furnace every two hours. The metal and slag are allowed to solidify and cool for six hours. It is then separated, crushed and screened to final size. The liquid metal and slag leaving the furnace at 1 550°C have a combined enthalpy of 6.2 GJ of thermal energy (estimate supplied by AlloyStream metallurgical department), a combination of latent and sensible heat.

Barati et al. estimated that 70% of thermal energy in the slag can be recovered [27]. In this study it is assumed that 50% of the thermal energy in the metal and slag, or 591 kJ/s, can be recovered by using thermal oil as the cooling medium. An ORC working at 250°C could convert 20% of the thermal energy into electricity at an average power of 118 kW. A large reservoir of thermal oil will be required and significant engineering challenges will have to be overcome to safely extract the heat from the metal and slag.

The estimated capex cost is R30 000/kW for the ORC, R3 000/(kJ/s) for the heat exchanger and R500/kJ/s for the oil, piping and pumps, giving a total of R5 720 000. The cooling water cost will be about R25/hour and the electrical cost related to the oil pumping circuit will be R10/hour. The system will have a high safety risk. The system will also be more complex than the existing naturally air-cooled solution. The payback period is eight to nine years. The social value is deemed high.

- Safety score = 5, low confidence.
- Financial score = 5, confident.
- Reliability score = 4, low confidence.
- Social score = 7, low confidence.

3.3.15 ECM13 – Use waste heat to electricity from some of the furnace cooling circuits

ECM13 is a logical progression from ECM7. Instead of rejecting the heat from the hot oil to atmosphere the heat is transferred to an ORC and electricity is generated. The heat harvested in addition to the off-gas thermal energy (ECM11) will be from the roof, sidewall and slag-line coolers. The waste heat rejected below the copper coolers is not considered. About 1 409 kJ/s thermal energy can be collected with thermal oil at 300°C. An ORC with an efficiency of 20% will generate 281 kW. The oil and water pump power is estimated at 75 kW.

The water usage is estimated as 1.6 kl/hour, thus adding R40/hour to the operating cost. The additional capex is estimated as R10 080 000. The safety risk profile should be better than ECM12, but worse than ECM11d. Reliability should be similar to ECM11d. The payback period is seven to eight years. The social value is deemed significant.

- Safety score = 6, confident.
- Financial score = 6, confident.
- Reliability score = 7, confident.
- Social score = 5, confident.

3.3.16 ECM14 – Recover pressure energy

Oxygen enters LP1 at 13 MPa and fuel gas enters LP1 at 0.6 MPa. This represents enthalpies of 39 kJ/s and 7kJ/s respectively that could be recovered with turbo-generators if the gas is not heated with waste energy. Only oxygen flow will be considered and heating is considered impractical. Typical efficiencies of turbo-generators are in excess of 80% [105]. 26 kW could be generated at a turbine efficiency of 80%.

The estimated capex is R2 500 000 for the specialised pipework and turbo-generator. The installation has some safety risk as pure oxygen handling can cause spontaneous combustion of components. The existing system will be retained as a back-up. The payback period is eleven to twelve years. The social value is deemed insignificant.

- Safety score = 6, confident.
- Financial score = 3, confident.
- Reliability score = 7, confident.
- Social score = 5, confident.

3.4 Evaluation

The evaluation method used by Athey discounts feasible solutions with the confidence rating. For example, ECM12 has a utility score of 99 and a discounted utility score of 22 due to the 0.2 overall confidence rating. An ECM with a high utility score (high total value) could, due to uncertainty, end up with a low discounted utility score. Solutions with high utility, but low discounted utility scores are therefore candidates for further research.

The results from the evaluation of the ECMs discussed in this chapter are shown in Table 4. The ECMs selected for implementation in LP2 are highlighted in the ECM column. The ECMs with the highest utility scores were selected. Except for ECM12, ECM13 and ECM14, the selected solutions also have the highest discounted utility scores. Further research is required on ECM12, ECM13 and ECM14 to increase the confidence rating. The full evaluation matrix is attached as Appendix B.

Table 4: Evaluation matrix totals

ECM		C	U	DU
1	Replace IE1 electrical motors with IE3	0.8	171	152
2	Upgrade inductor to high-efficiency configuration	0.8	130	115
3	Augment existing lights with light tubes	0.9	150	135
4	Convert solar radiation to electricity	0.7	127	95
5a	Install VSDs on all drives above 3 kW	0.7	173	140
5b	Low-pressure blast air system	0.8	159	129
6	Upgraded furnace roof refractory	0.8	140	124
7	Thermal oil-cooling of existing water-cooled circuits	0.7	102	78
8	Ore and coal preheating	0.4	71	31
9	Blast air preheating	0.5	115	58
10	Coal drying with waste heat	0.5	107	54
11a	Off-gas heat recovery with SC	0.5	113	66
11b	Off-gas heat recovery with BC	0.6	141	96
11c	Off-gas heat recovery with SRC	0.6	134	89
11d	Off-gas heat recovery with ORC	0.8	141	125
11e	Off-gas heat recovery with KRC	0.8	135	119
11f	Off-gas heat recovery with Brayton-ORC	0.6	128	86
12	Waste heat to electricity from metal and slag	0.2	97	22
13	Convert waste heat from ECM 7 to electricity	0.5	124	62
14	Recover pressure energy	0.5	106	53
C = Confidence rating, U = Utility rating, DU = Discounted utility rating (C x U)				

A number of technologies were not included in the list of ECMs considered. As mentioned before, any measure that could significantly affect the reduction process was rejected. Off-gas recirculation, briefly discussed in Chapter 6, is one such a measure. Reconfiguring the furnace geometry to reduce heat loss is another measure.

Thermoelectric generation (based on the Peltier effect) meets the constraints but the efficiency of commercially available high-temperature modules is below 8% [53, 54]. Wind power was not considered for LP2 because the location has a low wind intensity. Biomass as a replacement of coal could be an elegant option in areas where there is an abundance of water and land. Land is absent for LP2, water is not in abundance for FCP. Fuel cell technology was also not considered although the fuel gas could efficiently be converted to electricity for LP2 [106].

Finally, Athey states that one should keep looking for alternatives until the time runs out. The time ran out.

3.5 Conclusion

A number of energy efficiency strategies were developed into twenty ECMs. The performance of each measure was predicted and the utility score of each ECM was determined. The problem-solving approach identified the ECMs that should be implemented. It also revealed where lack of confidence significantly affected the relative worth of an ECM.

A comprehensive combination of ECMs is selected for implementation, and some synergy is apparent. The use of thermal oil, acting as a collector, conveyor and donor of thermal energy in ECM7 is a measure that positively influences a number of other ECMs. It may be inferred that an integrated approach is the best way to improve the energy efficiency of LP1.

CHAPTER 4

In Chapter 4 the energy flow in the existing plant is discussed. Fourteen ECMs are conceptually implemented to arrive at a new configuration that is more energy efficient.

If you would attain to what you are not yet, you must always be displeased by what you are. For where you are pleased with yourself there you have remained. Keep adding, keep walking, keep advancing.
~Saint Augustine

4 Current design and proposed conceptual design

4.1 Overview

Table 4 shows the measures selected for implementation to change LP1 to LP2. In the first step the unit processes indicated in the energy flow diagram for LP1 are analysed. Next the dependencies between the selected ECMs are identified. A conceptual redesign of LP1 is then done, resulting in a reconfigured, more efficient LP2. Fourteen ECMs were implemented and the result determined by updating the energy model and energy flow diagrams.

The plant energy efficiency excluding solar radiation (G2GEE1) of LP1 is 16,9%. The plant energy efficiency including solar radiation (G2GEE2) is 14.7%. The system energy efficiency (S2GEE) is 10.2%. The total energy entering the plant is on average 54 792 MJ/ton (including solar radiation). The total electrical energy entering the plant is 3 196 kW or 10 863 MJ/ton. The furnace receives 12 078 kJ/s or 40 637 MJ/ton total energy which is 74% of the total energy into the plant, and 2 106 kW or 66% of the electrical energy into the plant.

The energy flows from the source to the plant are indicated in Figure 8 and Figure 9. Although the study is focused on the energy efficiency of the plant, the plant's effect on the environment cannot be ignored. By modelling the primary energy flows external to the plant the effect on the environment of the plant energy efficiency improvement could be estimated.

4.2 LP1 energy flow

In Figure 8 each unit process is depicted as a rectangle and assigned a letter. The energy and mass entering and leaving the unit process is represented by a line and a number. The broken line represents the boundary of the Letaba plant. The values of the processes internal to the plant were taken from the forward calculator, actual values observed during campaign 1 and estimated values where values were not recorded. The values of external processes were calculated based on information obtained from literature.

The unit processes of LP1 are discussed in the sections that follow. To enable tracing from one unit process to the next the source output reference number is given in brackets. For example coal drying is assigned the letter *J*, wet coal is an input and assigned the letter *J1*. The upstream process delivering the coal to the dryer is coal transport *C*, the output of coal to the plant is *C2*, indicated as (*C2*).

In Figure 8 material and energy enters the plant from the top. Waste heat exits the plant to the left, material to the bottom. A basic energy balance was constructed for each unit process and an overall mass and energy balance calculated to assure reasonable accuracy. All energy flows have been converted to average instantaneous values.

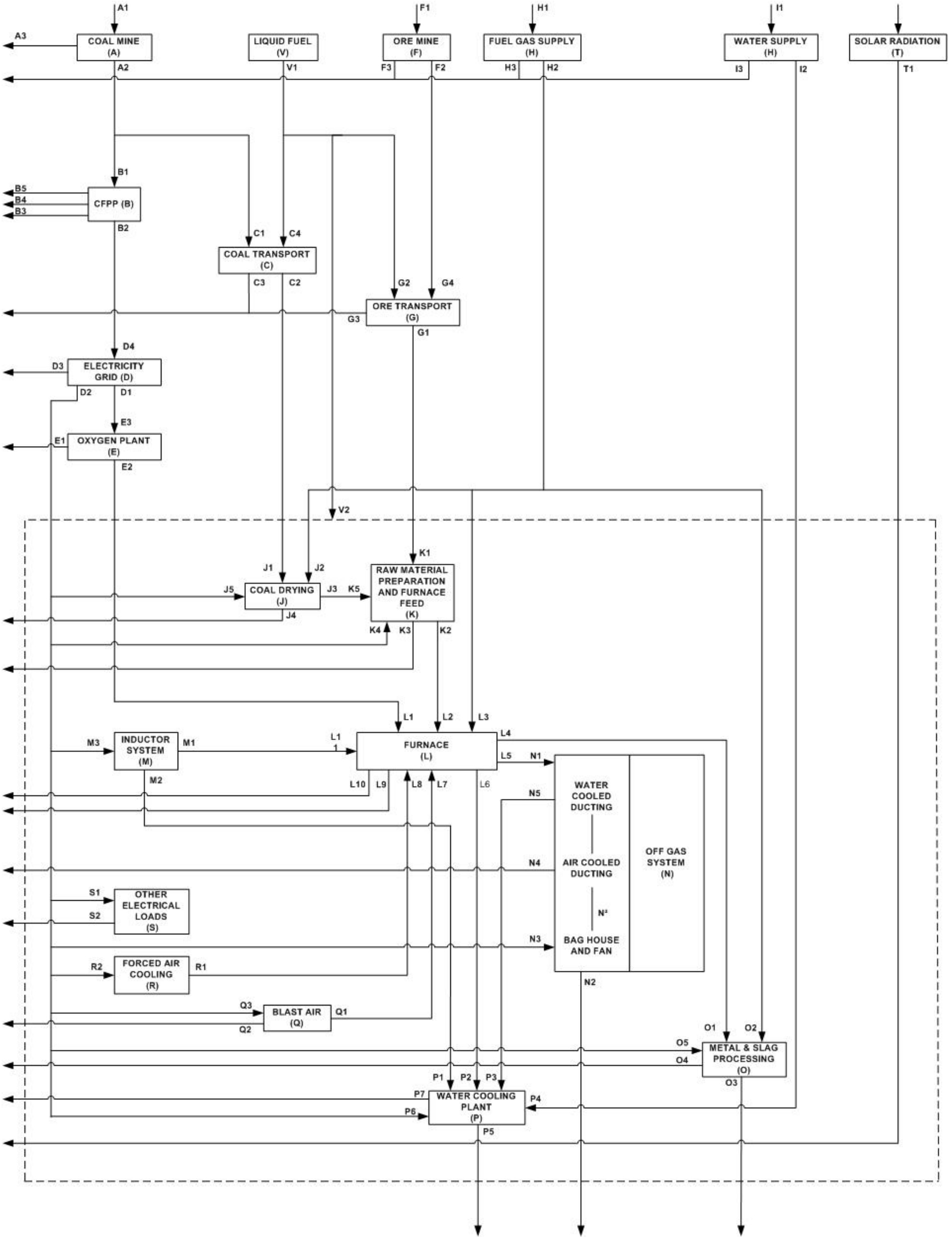

Figure 8: Energy and mass flow diagram for the current prototype plant LP1

4.2.1 Processes external to the plant

Coal mine (A)

The energy required to mine coal is 19.2 kJ/kg [107]. The coal mass flow from the mine is 0.67 kg/s. The energy content of the coal is 27 740 kJ/kg (higher heating value) with an ash content of 12.5% [108]. The moisture content is 12%. The mine is 80 km from LP1 and less than 10 km from the coal-fired power plant (CFPP).

Coal-fired power plant (B)

The thermal efficiency of the CFPP is 37.8% [109,110]. The coal flow to the CFPP to generate the electrical power required by LP1 is 0.36 kg/s. The electricity to grid is 3 746 kW, related waste heat to the environment is 6 165 kJ/s.

Coal transport to the plant from the mine (C)

Coal is transported from the mine to LP1 and LP2 via 30-ton road trucks. The fuel consumption is 40 litres per 100 km [111]. The fuel energy use is 40 kJ/kg coal, calculated over a distance of 80 km for a fully laden 30-ton truck. The coal mass flow to LP1 is 0.31 kg/s.

Electricity grid (D)

The distribution and transmission loss from Eskom is 4.61% [112], compared to the US Energy Information Administration’s loss of 7% [113]. The distribution and transmission losses (based on the value from Eskom) amount to 165 kW.

Oxygen plant (E)

Oxygen is generated by a supplier in a cryogenic plant very close to LP1. Typical medium capacity plants use 0.5 kWh/Nm^3 to 0.55 kWh/Nm^3 electrical power [114]. For this study 0.55 kWh/Nm^3 will be used for LP1 and LP2. The mass flow to LP1 is 0.28 kg/s at 1 300 kPa.

Ore mine (F)

The energy required to mine ore is 56 kJ/kg [115]. The ore mass flow from the mine is 0.62 kg/s. The mine is 620 km from Letaba.

Ore transport (G)

Ore is transported from the mine to LP1 and LP2 using 30-ton road trucks. The fuel consumption is 320 kJ/kg ore, calculated over a distance of 640 km [111]. The ore mass flow to LP1 is 0.62 kg/s.

Fuel gas supply (H)

Fuel gas from a natural gas field is supplied to LP1 and LP2 via a 700-km pipeline at a pressure of 600 kPa. The energy content of the gas is 36 100 kJ/kg (LHV) [116]. The energy required to extract and transport the gas was not estimated. The gas mass flow to LP1 is 0.06 kg/s.

Water supply (H)

Water is supplied to LP1 and LP2 via pipeline at 1 300 kPa. The mass flow to LP1 is 2.22 kg/s. The pressure energy of the water as delivered to LP1 is 2.89 kW. The water used at the CFPP to generate the electrical power used by LP1 is estimated as 2.52 kg/s. Only the pressure energy entering the plant was considered.

Liquid fuel (V)

Liquid fuel use was considered only for the ore and coal transport, as well as material movement inside the plant. The total liquid fuel use for transport of coal and ore is 17 kg/hour. The liquid fuel consumption in LP1 and LP2 is estimated as 9 kg/hour, as confirmed by the financial manager of AlloyStream.

4.2.2 Processes internal to the plant

Coal drying (J)

- Inputs:
  - J1 – wet coal, 12% water content (C2)
  - J2 – fuel gas, 5 g/s (H2)
  - J5 – electricity use, 12 kW (D2)
- Outputs:
  - J3 – dry coal, 3.6% water content, 27 652 kJ/kg LHV, mass flow 0.29 kg/s
  - J4 – waste heat to environment,181 kJ/s

Raw material preparation and furnace feed (K)

- Inputs:
  - K1 – ore mass flow, 0.62 kg/s (G1)
  - K4 – electricity use, 45 kW (D2)
  - K5 – coal mass flow, 0.29 kg/s (J3)
- Outputs:
  - K2 – raw material mix, mass flow 0.91 kg/s
  - K3 – waste heat to environment, 45 kJ/s

Inductor system (M)

- Inputs:
    - M3 – electrical power to transformer and drive, 2 150 kW (D2)
- Outputs:
    - M1 – heat to bath from inductor, 1 411 kJ/s
    - M2 – waste heat to water, 853 kJ/s

Forced air-cooling of shell (R)

- Inputs:
    - R2 - electrical power, 35 kW (D2)
- Outputs:
    - R1 – air mass flow to furnace shell, 10 kg/s

Blast air (Q)

- Inputs:
    - Q3 - electrical power, 364 kW (compressor-based)
- Outputs:
    - Q1 – mass flow to furnace 0.85 kg/s, pressure 7.5 bar (g)
    - Q2 – waste heat to environment, 364 kJ/s

Furnace (L)

- Inputs:
    - L1 – oxygen mass flow, 0.28 kg/s at 1 300 kPa (E2)
    - L2 – raw material feed, 0.91 kg/s (K2)
    - L3 – fuel gas flow, 0.06 kg/s (H2)
    - L7 – blast air flow, 0.85 kg/s (Q1)
    - L8 – forced air-cooling, 10 kg/s (R1)
    - L11 – electromagnetic power from inductor to bath, 1 411 kW (M1).
- Outputs:
    - L4 – metal flow 0.29 kg/s, enthalpy 1 954 kJ/kg, slag flow 0.21 kg/s, enthalpy 1 394 kJ/kg
    - L5 – off-gas flow 1.73 kg/s, c_p = 1.38 kJ/kg.K, sensible heat 3 693 kJ/s, temperature 1 550°C; radiation heat transfer to off-gas ducts 521 kJ/s
    - L6 – waste heat to water, 3 413 kJ/s
    - L9 – waste heat to air from natural air-cooling, 155 kJ/s
    - L10 – waste heat to air from forced air-cooling, 113 kJ/s

Off-gas (N)

- Inputs:
    - N1 – off-gas from furnace, 3 693 kJ/s (L5)
    - N3 – electrical power, 85 kW (D2)
- Outputs:
    - N2 – sensible heat to atmosphere through stack, 392 kJ/s
    - N4 – waste heat to atmosphere from air-cooled ducting, 931 kJ/s
    - N5 – waste heat to water, 2 890 kJ/s (including radiation heat from furnace)

Metal and slag processing (O)

- Input:
    - O1 – metal and slag from furnace 0.5 kg/s, total enthalpy 866 kJ/s, temperature 1 550°C (L4)
    - O2 – fuel gas for mould drying, 0.002 kg/s (H2)
    - O5 – electrical power, 10 kW (D2)
- Output:
    - O3 – metal and slag mass flow 0.5 kg/s
    - O4 – waste heat from mould drying, 316 kJ/s, waste heat from metal and slag cooling 866 kJ/s; waste heat from crushing plant 10 kJ/s

Water-cooling plant (P)

- Inputs:
    - P1 – waste heat from inductor system, 853 kJ/s (M2)
    - P2 – waste heat from furnace, 2 560kJ/s (L6)
    - P3 – waste heat from off-gas water-cooled ducting, 2 890 kJ/s (N5)
    - P4 – make-up water, 2.4 kg/s (I2)
    - P6 – electrical power, 225 kW (D2)
- Output:
    - P5 – vapour to atmosphere 1.98 kg/s, waste heat 6 049 kJ/s
    - P7 – blow-down water, 0.24 kg/s

Other electrical (S)

- Input:
    - S1 – electrical power, 250 kW (D2)
- Output:
    - S2 – waste heat, 250 kJ/s

Solar radiation (T)

- Input:
    - I2 – average solar radiation 5 kWh/m^2 per day, 10 000 m^2, 2 083 kJ/s on average
- Output:
    - I2 – waste heat to atmosphere 2 083 kJ/s on average

Liquid fuel (V)

- Input
    - V2 – mean energy into plant 110 kJ/s
- Output
    - Not shown on diagram – waste heat 110 kJ/s

The ECM evaluation in Chapter 3 was done assuming that each ECM is a standalone solution, in other words there is no synergy or conditional relationships: the ECMs are independent. This assumption is not valid when a combination of ECMs is implemented. To reveal the relationships amongst the selected ECMs (see table 4) a basic dependency analysis was done, the results are summarised in Table 5.

From the dependency analysis in Table 5 it is clear that ECM7 favourably affects a number of other ECMs. Conceptual implementation of the selected ECMs resulted in a modified energy flow shown in Figure 9.

.

Table 5: ECM dependency table

ECM number	**Affected by**	**Effect**
ECM1 – High-efficiency motors	ECM5a, ECM5b and ECM7	All three ECMs will reduce total motor power and thus the saving attributed to ECM1.
ECM2 – Inductor upgrade	Independent	
ECM3 – Light tubes	Independent	
ECM4 – Solar PV	Independent	
ECM5a – VSDs	ECM7	ECM7 will reduce the cooling water pump power substantially and thus reduce the energy savings predicted for installing VSDs on the main pump drives.
ECM5b – Low-pressure blast air	Independent	
ECM6 – Low heat loss roof refractory	ECM7	The heat loss reduction due to ECM6 will be slightly affected by ECM7.
ECM7 – Cooling by thermal oil	ECM6	The heat loss reduction through the roof due to ECM6 substantially reduces the heat loss achieved by ECM7.
ECM9 – Preheat blast air	ECM7, ECM11d, ECM12 and ECM13	Hot thermal oil is available.
ECM10 – Dry coal with waste heat	ECM7, ECM11d, ECM12 and ECM13	Hot thermal oil is available.
ECM11d – ORC	ECM7, ECM12 and ECM13	Hot thermal oil is available.
ECM12 – Recover waste heat from metal and slag	ECM7, ECM11d and ECM13	Hot thermal oil is available.
ECM13 – Recover waste heat from furnace cooling circuits	ECM7, ECM11d and ECM12	Hot thermal oil is available.
ECM14 – Recover pressure energy from oxygen	Independent	

4.3 Proposed conceptual design (LP2)

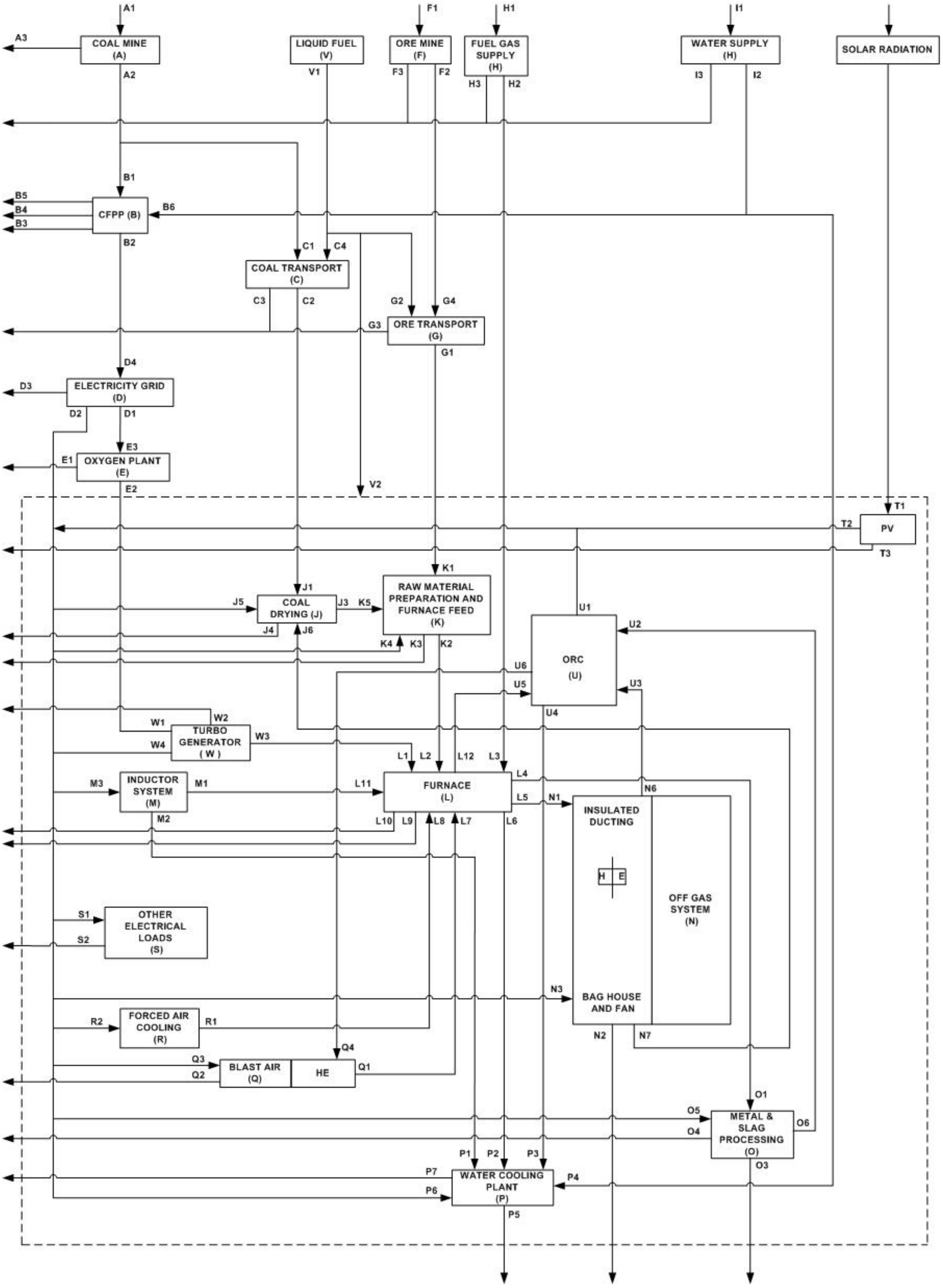

Figure 9: Energy and mass flow diagram for the redesigned prototype plant LP2

Only changes from the LP1 to the LP2 configuration are discussed in the sections that follow.

Coal drying (J)

In LP1 coal is dried using a hot air-to-coal heat exchanger. The air is heated by combusting fuel gas. By implementing ECM10 in LP2 the coal will be dried by a heat exchanger that transfers thermal energy from thermal oil to the coal. This could be accomplished through retrofitting the existing dryer or by installing a different unit. The thermal oil will be heated with waste heat from the off-gas system after the bag-house where the off-gas temperature is below 250°C (N7 to J6). The net effect is a reduction of 5 g/s (energy equivalent of 181 kJ/s) in fuel gas use (H2), and an estimated increase in electricity use of 5 kW required to circulate the oil between the off-gas system and the coal dryer.

Inductor system (M)

By upgrading the inductor installed in LP1 to a high-efficiency configuration (ECM2) the efficiency of conversion of electricity to electromagnetic energy transferred to the liquid metal bath increases from 66% to 71%. This results in a 49 kW electrical load reduction (M3) and a 49 kJ/s reduction in waste heat to the cooling water system (M2).

Blast air (Q)

ECM5b replaces the high-pressure compressor system used in LP1 with a low-pressure blower system. As a result the electricity use reduces by 316 kW from 364 kW for the compressor system to 48 kW for the blower system (Q3).

No blast air preheating is done in LP1. ECM9 preheats the blast air to 250°C in LP2 (U6 to Q4). A 15% reduction in oxygen use is predicted (E2).

Furnace (L)

ECM6 will reduce the roof heat loss from 1 079 kJ/s to 350 kJ/s (L6 to P2). ECM7 replaces the water-cooling for most furnace circuits with thermal oil at an average temperature of 300°C (L12 to U5). The combined effect of ECM6 and ECM7 is a reduction in fuel gas use of 30 g/s (H2 to L3), electrical power to the water-cooling system reduces by 45 kW (P6) and water consumption reduces by 1 kl/hour (P4).

Off-gas (N)

ECM11 transfers most of the thermal energy in the gas stream to thermal oil which in turn powers an ORC (N6 to U3).

Metal and slag processing (O)

In LP1 metal and slag are tapped on average every two hours into multiple 170-litre refractory lined moulds. The mixture is allowed to solidify and cool for a six-hour period before the moulds are emptied. The LP1 metal and slag handling system has a number of deficiencies, and a new system that will enable heat recovery as a secondary objective is being developed. ECM12 aims to recover 50% of the available thermal energy, or 591 kJ/s, with thermal oil heat exchangers and convert the thermal energy into electricity through an ORC (O6 to U2). In addition the new casting technique in combination with the thermal oil system will remove the need for mould drying, resulting in a reduction in fuel gas use of 2.4 g/s (H2).

Water-cooling plant (P)

Implementation of ECM1, ECM2, ECM5a, ECM6, ECM7, ECM11d, ECM12 and ECM13 has a significant impact on the water-cooling plant. The total water usage reduces from 2.4 kg/s to 1.8 kg/s (P4) and the electrical power required to pump the water and oil and drive the cooling tower fans reduces from 245 kW to 169 kW (P6).

Other electrical (S)

The LP1 load of 250 kW reduces to 240 kW due to the implementation of ECM3 (S1).

Solar PV (T)

ECM4 generates an average electrical power of 67 kW (T2).

ORC (U)

All thermal energy collected by the thermal oil (U2, U3 and U5) minus the energy needed for blast air heating (U6 to Q4) enters the ORC. 20% is converted to electricity (U1); the balance is rejected to the water-cooling plant (U4 to P3). Power required to circulate the thermal oil is included in the plant output calculation. The ORC produces 935 kW net.

Turbo-generator (W)

A turbo-generator that recovers pressure energy from the oxygen supply (ECM14) is installed in LP2. The device generates 26 kW electrical power (W4).

4.4 Evaluation

The implementation of a combination of ECMs changed the energy reduction predicted in Chapter 3 but not the payback period, safety and/or social scores. In Table 5 the results of the conceptual redesign are shown. The values for LP1 are from the forward calculator [9]. The values for LP2 are from the spreadsheet used to model the conceptual design.

Table 6: Results of ECM conceptual implementation

Parameter	**LP1**	**LP2**
Electricity into plant	10 863 MJ/ton	5 705 MJ/ton
Fuel gas energy into plant	7 830 MJ/ton	2 791 MJ/ton
Fuel gas use	217 kg/ton	77 kg/ton
Oxygen use	939 kg/ton	798 kg/ton
Water use	16.8 kl/ton	10.9 kl/ton
Total energy into plant, excluding solar radiation	46 199 MJ/ton	35 944 MJ/ton
Reduction energy required	7 826 MJ/ton	7 826 MJ/ton
G2GEE1	16.9%	21.8%
G2GEE2	14.7%	18.2%
S2GEE	10.2%	13.7%
Fuel gas cost	R 651/ton	R232/ton
Electricity cost	R3 017/ton	R1 584/ton
Note: Electricity unit cost is100 cents/kWh, fuel gas cost is 300 cents/kg. All values are per ton of metal produced.		

The implementation of fourteen ECMs changed the energy efficiency of LP1 substantially. The reduction in grid power resulted in a substantial opex reduction. Some ECMs reduced the use of fuel gas only, some the use of electricity only; the balance reduced both. The dominant improvement was achieved by capturing (or harvesting), waste heat with thermal oil. By implementing a thermal oil system the heat loss from the furnace was reduced and electricity generation by a heat engine enabled. The percentage reduction in energy cost is much more than the percentage energy reduction, illustrating the significant difference in cost of the two energy sources.

In practice it is unlikely that all the ECMs will be implemented at the same time. A logical sequence of implementation is as follows:

1. Implement ECM3 and ECM4.
   They are independent of the others and do not require a shutdown of the plant.
2. Implement ECM10.
   ECM10 does not affect any critical furnace components.
3. Implement ECM5a and ECM11d.
4. Implement ECM12 and ECM14.
5. Implement ECM2, ECM6 and ECM7 during a shutdown.
6. Implement ECM1 when the final motor capacities are known.

4.5 Conclusion

The energy flow of LP1 was analysed and reconfigured by conceptually implementing fourteen ECMs. The integrated conceptual design created LP2. The energy efficiency increased from 18% to 23% thus answering Question 3 of the problem statement (To what level can it be improved?); and the energy cost of the plant decreased. The input energy was reduced by more than 9 000 MJ/ton proving that Hypothesis 2 is conceptually true (the energy use of the plant can conceptually be reduced by more than 5 000 MJ/ton). A logical implementation sequence was also proposed.

CHAPTER 5

In Chapter 5 the results of the conceptual redesign and the measurement and verification approach are discussed. The two measures that were implemented are described and evaluated.

No man has a good enough memory to make a successful liar.
~Abraham Lincoln

5 Results

5.1 Overview

Two plants have been built and operated by AlloyStream to date. The first plant was called Rivet, the second (and currently in operation) is Letaba. Rivet's main purpose was to verify the theoretical ore reduction model whereas Letaba's main purpose is to demonstrate the technology on a pre-commercial scale. Rivet was extensively instrumented and the instrumentation was retained at Letaba.

In Chapter 4 a number of ECMs were conceptually implemented on LP1 to arrive at a new plant configuration called LP2. Two measures were also designed and implemented on Letaba to date. The two measures are described and the results of their implementation discussed in sections 5.5 and 5.6.

When Rivet was upgraded to Letaba a more energy efficient water-cooling system was designed and constructed. Between Letaba campaign 1 and Letaba campaign 2 the compressor-based blast air system was replaced with a low-pressure blower system. This chapter discusses the overall measurement and verification approach followed to date in the development of the AlloyStream^{TM} technology and the measurement and verification of the energy model and the two implemented measures.

5.2 Results from the conceptual design

In Chapter 1, Section 1.4 the problem to be addressed by this study was stated as three questions:

1. How can the energy efficiency of the ore reduction plant on which the study is based be measured?
2. Which is the best way of improving the energy efficiency?
3. To what level can it be improved?

In Chapter 2, Section 2.6 Question 1 was answered. In Chapter 4, Section 4.4 Question 2 and Question 3 were answered.

Two hypotheses were also formulated in Chapter 1, Section 1.4: the energy efficiency can be measured (Hypothesis 1) and the energy use of the plant can be reduced by more than 5 000 MJ/ton (Hypothesis 2).

In Chapter 2, Section 2.6 Hypothesis 1 was proven true. The conceptual integrated redesign of the plant resulted in an input energy reduction of more than 5 000 MJ/ton, indicating that Hypothesis 2 has a high likelihood of being true.

The study has found (with some confidence) that without affecting the reduction process the:

- Electrical energy purchased by the Letaba plant can be reduced by up to 47%
- Fuel gas use can be reduced by 64%
- Water consumption can be reduced by 35%

5.3 Plant-wide measurement and verification

AlloyStream is an ISO 9002 qualified organisation. All important business processes are described, documented and regularly reviewed. Design management, and process measurement and verification are critical sub-processes and managed as such.

The process followed to establish Rivet and Letaba was:

1. Estimate the furnace dimensions.
2. Populate a spreadsheet (forward calculator) with the dimensions and selected ore and coal characteristics.
3. Adjust the dimensions and recalculate until a workable solution is found.
4. Perform computational fluid dynamics modelling of the combustion chamber to determine the optimum lance and feed port configuration.
5. Write a functional requirement document that serves as a key engineering design input.
6. Create process flow diagrams that show the important mass and energy flows as well as maximum, aim and minimum values for the important variables. Then create process and instrumentation diagrams.
7. Create other key documents such as drawings and specifications, and obtain approval from a review committee before release for manufacturing.
8. Manufacture and construct and commission.
9. Verify the actual performance against the functional requirements during final commissioning.
10. Measure and compare actual measured values during operation with the predicted values and analyse deviations.
11. Generate a comprehensive report after each campaign, for example the Letaba campaign 1 Process Report. Extracts from this report appear in the appendices.

The Letaba plant has over 2 500 measurements that are captured by a process control system continuously. The variables relevant to this study (in bold) and background variables are discussed in the sections that follow.

Inbound and outbound logistics:
Ore and coal are delivered by 30-ton road trucks and stored on-site. Ore is stored in an enclosed store; coal is stored on an open concrete slab. The mass of each delivered load is determined by pre- and post-weighing of the trucks at the mines.

Fuel gas enters the plant via a pipeline at a pressure of between 4 and 6 bar. Three mass flow meters, one on the supplier's side and two inside the plant, are used to determine the flow of gas. The supplier's meter is calibrated annually and the accuracy is considered better than 97%. The internal meters determine the gas flow to the coal dryer and the flow to the furnace gas distribution system.

Oxygen enters the plant via a pipeline at a pressure between 9 and 16 bar. One mass flow meter, situated inside the plant, is used to determine the flow. The meter measures pressure with a pressure transducer, temperature with a platinum resistance thermometer (Pt-100) and gas velocity with a Pitot tube-type instrument. The differential pressure obtained from the Pitot tube is sensed by a differential pressure transducer. The change in values of all three field instruments is converted to 4 – 20 mA signals by constant voltage supplies. Analogue to digital converters then convert the analogue signals to digital values; these are recorded by the central processing system. The flow of gas is calculated using the ideal gas equation and displayed and recorded in normal cubic metres/hour. Normal is defined by ISO 10780 as the volume in cubic metres at 0°C and 101.325 kPa. This standard is applied throughout the plant for gas flow measurement.

Electricity is supplied by two 11 kV sub-stations. The plant is billed by the supplier on an energy basis; no maximum demand charge is levied. Measurement is done using two kWh meters.

Water enters the plant through a pipeline at 13 bar. The water usage is measured by a standard water meter. The plant is billed for the water use as well as for sanitation, which is calculated pro rata from the water consumption.

Samples are taken from the tap stream and analysed by an ISO-certified laboratory. Slag and metal are transported from the plant by road trucks. The mass leaving the plant is determined at the plant by weighing the loads on the trucks with platform scales. The scales are calibrated annually by a certified external party. The scale accuracy is considered better than 97%.

Internal mass and energy measurement:

Off-gas mass flow is not measured; instead it is determined with a comprehensive mass and energy balance that relies on the measurement and characteristics of the input materials to the furnace, as well as measuring the off-gas composition and temperature. The accuracy is estimated as better than 90%.

Coal mass flow is determined by batch weighing in weigh flasks mounted on load cells. The weighing systems are calibrated at least annually by a certified supplier. The accuracy is considered better than 98%. All coal enters the furnace; about 2% leaves the furnace as dust in the off-gas, as does some ore. The mass of coal and ore that is removed from the off-gas system is determined by weighing it before it is dispatched to a disposal dump.

Electricity supplied to the inductor is accurately measured and recorded by the inductor control system. No other electrical loads are measured and recorded continuously.

All cooling water flows are measured with magnetic flow meters. Temperature is measured with Pt-100 devices. The flow and temperature measurement accuracy is considered better than 97%.

Refractory temperature is measured at various points with various types of thermocouples.

The liquid bath temperature is measured with sacrificial probes.

Ambient temperature measurement is with a Pt-100. Ad-hoc surface temperature measurements are taken with handheld infrared meters and a thermal camera.

Effect of situational variables

An operating plant never runs on one operating point – there is simply too much variation in the parameters that affect performance. Some of the key parameters that affect especially energy efficiency are:

- Ambient temperature, especially wet bulb temperature will affect the efficiency of the proposed ORC heat engine.
- Ore characteristics significantly affect the recovery from ore and the rate of production of metal.
- Coal characteristics significantly affect the behaviour of the combustion zone and the ratio of ore to coal and hence the coal to metal ratio.

- Variations in the metal production rate affect the bath temperature; this in turn affects electrical power input to the inductor.
- Refractory deterioration with time increases the heat loss through the furnace walls and from the bath to the inductor coil.
- Equipment malfunction and operator error disturbs the steady-state conditions.

In this study the key situational variables are fixed by the input documents mentioned before. The model is based on only one theoretical steady-state operating point and the actual recorded values have therefore no significant effect on the predicted LP2 performance. During Letaba campaign 1 departure from the operating point were recorded. The metal production rate was less than predicted by the forward calculator and the fixed value in the model (1.07 ton/hour). The result is that the actual energy required by the plant to produce a ton of metal varied from the value in the model by up to +15%.

5.4 Measurement and verification of the conceptual model

As discussed in Section 2.6 the process energy used in equation 7 should be the metal and slag exergy. In this study an approximation of the product exergy is made by approximating it with the process enthalpy calculated by Tangstad and Olsen [1].

The energy efficiency of the plant is determined by the equation:

Equation 7: Energy efficiency of the plant

$$\eta = \text{process entalpy}/\text{input energy}$$

This is the dependent variable of the model. Since the process entalpy is held constant the input energy is the only independent variable in the equation. The input energy is in turn a function of the use of fuel gas and electricity use only, as the coal consumption is kept constant. The energy efficiency therefore has only two independent variables – fuel gas and electricity use. Conceptual implementation of the ECMs adjusted one or both independent variables. The sensitivity of the dependent variable to changes in the ECM saving is important, thus more attention was given to verification of ECMs that have a high impact on the predicted energy efficiency of LP2.

A manual modelling process using a spreadsheet was followed. The spreadsheet formulas are the only “automated” calculations. The spreadsheet model requires some insight to manipulate correctly. The simplicity of the approach, however, enabled results to be obtained relatively quickly and at low cost.

The spreadsheet accuracy was verified with repeated checking and applied logic. The approach is illustrated in appendix J.

To model the performance of LP1 an energy balance for each unit process was aimed for, but due to time constraints only done for the furnace, inductor system, off-gas and water plant. Following the selection of ECMs for conceptual implementation the spreadsheet model was reworked to determine LP2 performance. This proved to be an iterative process that increased the confidence in the values used.

The use of the energy diagrams played a vital role. By having visual presentation the subject could quickly be explained to other people and discussions conducted productively. The total energy input to LP1 is 13 593 kJ/s and 10 575 kJ/s for LP2, excluding solar radiation. ECM6, ECM7 and ECM11d are the only ECMs that have an energy conservation contribution of more than 4% of the LP2 energy input. Variation of the modelled performance of any ECM within ±20% will not cause a change in plant input energy of more than 1% ($0.2 \times 4 = 0.8 < 1$). It is therefore concluded that inaccuracies within ±20% in the modelled performance of individual ECMs will not have a significant effect on the predicted LP2 efficiency.

Bias affects all ECMs and could have a significant effect. As an example a consistent 10% optimistic bias would change the LP2 G2GEE1 from 22% to 24%. To counteract optimistic bias a conservative approach was followed. For example, the electricity generated by the ORC is reduced by the pinch temperature difference between the off-gas leaving the heat exchanger and the thermal oil entering the heat exchanger. A temperature difference of 80°C was used in the model, even though all literature sources referenced use temperature differences of less than 40°C. The general approach was that where literature sources differed regarding values, the conservative value quoted was used in the model, or a more conservative value was used.

A comprehensive campaign report was compiled after Letaba campaign 1 by the AlloyStream process department [117]. The values below are from that report. The corresponding values used in the model are shown in brackets.

The recorded flow rates of blast gases (oxygen, fuel gas and air) during LP1 campaign 1 are shown in Appendix D. The average flow rates over the campaign (design aim values in brackets) was 1 754 Nm^3/hour (2 500) for blast air, 728 Nm^3/hour (800) for oxygen and 290 Nm^3/hour (250) for fuel gas. The off-gas flow during campaign 1 is shown in Appendix E. The average flow rate was calculated as 2 098 Nm^3/hour (4 822). Towards the end of the campaign the flow rate was 4 000 Nm^3/hour, or 20% less than used in the model. The actual sensible heat available from the off-gas reduces correspondingly. The heat losses from the upper part of the furnace increased significantly during the campaign, the increase in heat loss through the roof being the most significant (Appendix F). The roof loss increased from 662 kJ/s to 1 458 kJ/s (1 079) during the campaign.

The calculated process energy varied between 4 659 kWh/ton and 3 796 kWh/ton primarily due to the lower than predicted metal production rate (Appendix G) which effectively reduces the thermal efficiency of the combustion chamber and bath heating. The value used in the model is 2 174 kWh/ton. The inductor input power approached the model power of 2 106 kW towards the end of the campaign (Appendix H). The metal production rate varied between 770 and 990 kg/hour. The value used in the model is 1 070 kg/hour.

Accuracy of the predicted performance of the ECMs

The systematic systems approach attempts to compensate for inaccuracies due to uncertainty by discounting an ECM’s relative worth with the uncertainty rating. This approach results in a conservative assessment – uncertainty reduces the relative worth in all cases. In practice, uncertainty in project costing is dealt with by attaching an accuracy estimate to costs, always a plus and minus value. Each organisation has its own rules. For AlloyStream the required accuracy of costing during concept design phase is +30% to -20%.

The relative values of the safety, reliability and social scores were subjectively determined, primarily by the author as analyst. The safety scores were reviewed by a panel to improve confidence. Athey identifies three cases depicting the analyst’s expertise on the problem studied [77]:

- Case 1: analyst has full expertise
- Case 2: analyst has no expertise
- Case 3: analyst has limited expertise

For this study the author selected Case 3 as the most appropriate.

Athey recommends answering the following four questions to evaluate information [77]:

- What is it?
- Does it make sense?
- How competent is the source?
- How credible is the source?

His method has been used as thoroughly as possible to evaluate the information and arrive at the confidence levels discussed in Chapter 3. In addition, an iterative approach was followed to verify the predicted results with most time spent on the ECMs that yielded the best results. The development and refining of the flow diagrams and quantifying of the values in a spreadsheet model assisted the process of verification.

5.5 Low-pressure blast air system

During the five Rivet campaigns and the first Letaba campaign blast air was provided with two Compair L250 screw compressors that operated in parallel. Each compressor had a maximum power draw of 250 kW. The standard compressors rating is at an inlet pressure of 100 kPa and temperature of 15°C. A flow diagram of the compressed air supply system is shown in Figure 10.

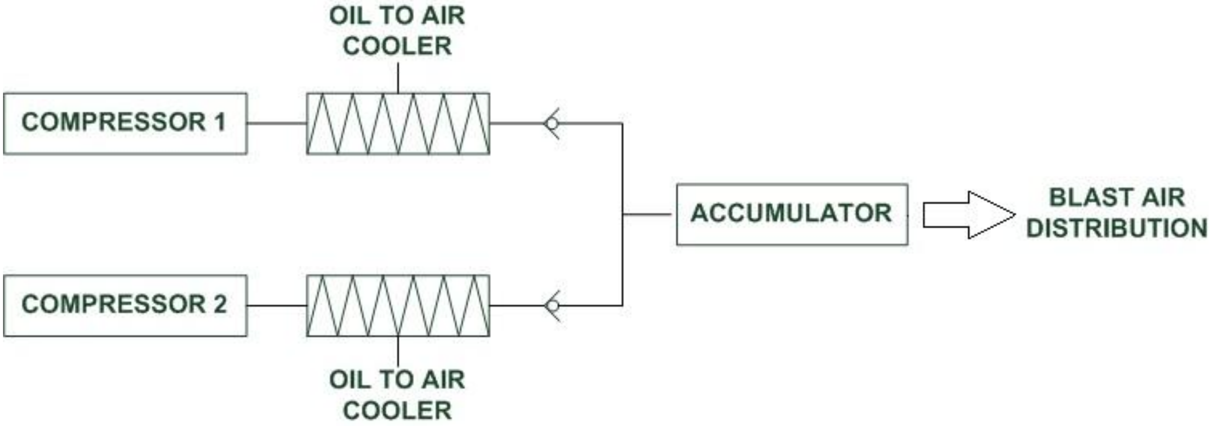

Figure 10: Compressed air supply system

In Letaba campaign 1 both compressors were run simultaneously. One compressor was set to a higher delivery pressure than the other (typically 50 kPa). This caused the “high” compressor to run continuously at load and the “low” compressor to cycle in and out when required. A basic calculation to determine the power draw is shown in Appendix H. The electrical power, assuming no air leakages and a no-load power draw of 20% full load, was found to be 364 kW at a delivery of 2 500 Nm³/hour.

During the design of Letaba the high electrical energy use of the blast air system based on compressors was recognised. The compressor-based system was, however, retained due to time and capital fund constraints. Alternatives that are more energy efficient were investigated and two promising options identified: Rootes-type blowers that deliver the required flow at up to 85 kPa, and high-pressure centrifugal fans (called blowers) that delivers the required flow at up to 40 kPa in single-stage configuration.

The blast air supply system had to meet the following requirements:

- Minimum pressure: to prevent flow reversal in the lances during a pressure rise inside the furnace the system must maintain a minimum pressure of 1 kPa
- Low energy use
- Accurate flow control
- High reliability
- Minimum space requirement
- Low noise
- Low purchase cost and low maintenance cost
- Accurate flow measurement

With the premature termination of campaign 1 and the subsequent downtime of about nine months, an opportunity presented itself to upgrade the compressed air system to a more energy efficient system. The centrifugal blower option was selected on the basis that it met all the requirements with a lower energy use and considerably less capex than the Rootes blowers. A distributed approach (one blower per lance) rather than a central system was selected, because a central system (with say two blowers) would require a control valve for each line and low-cost valves and actuators could not be found in time. To meet the flow control requirement each blower motor is driven with a VSD with a speed range of 40% to 120% rated motor speed. A blower curve is attached in Appendix I.

To achieve accurate flow measurement hot wire anemometers were selected. Problems were experienced with the pitot tube-type flow meters used in the compressed air system during campaign 1. Also, hot wire anemometers were less expensive. The reliability of the hot wire anemometers still needs to be proven. A picture of the system is shown in Figure 11.

Before commissioning of the system a series of tests were conducted with one blower and lance. A configuration identical to the operational system was set up and run at various blower speeds. The ambient temperature was recorded during the test and varied by less than 5°C. The static pressure was measured with a pressure transducer at the blower discharge and at entry to the lance. Air velocity was measured with a calibrated hot wire anemometer positioned in the straight inlet pipe with thirty pipe diameters upstream and twenty pipe diameters downstream of the anemometer.

The results obtained with the initial test confirmed that the actual performance deviated by less than 6.5% from the standard blower curve (Appendix I) under actual conditions. The actual blower pressure at 209 Nm³/hour flow rate with the non-return valves, hoses and lance fitted was between 25 kPa and 30 kPa and the power draw 4 kW per blower. The total blower power used in the model is therefore 48 kW. The reduction in electrical use from compressors to blowers is calculated as 316 kW. At the 2013 electricity cost of R1.00/kWh an energy cost saving of R 316/hour or R2 686 000 per year is realised. The material and engineering cost was between R1.45m and R1.55m.

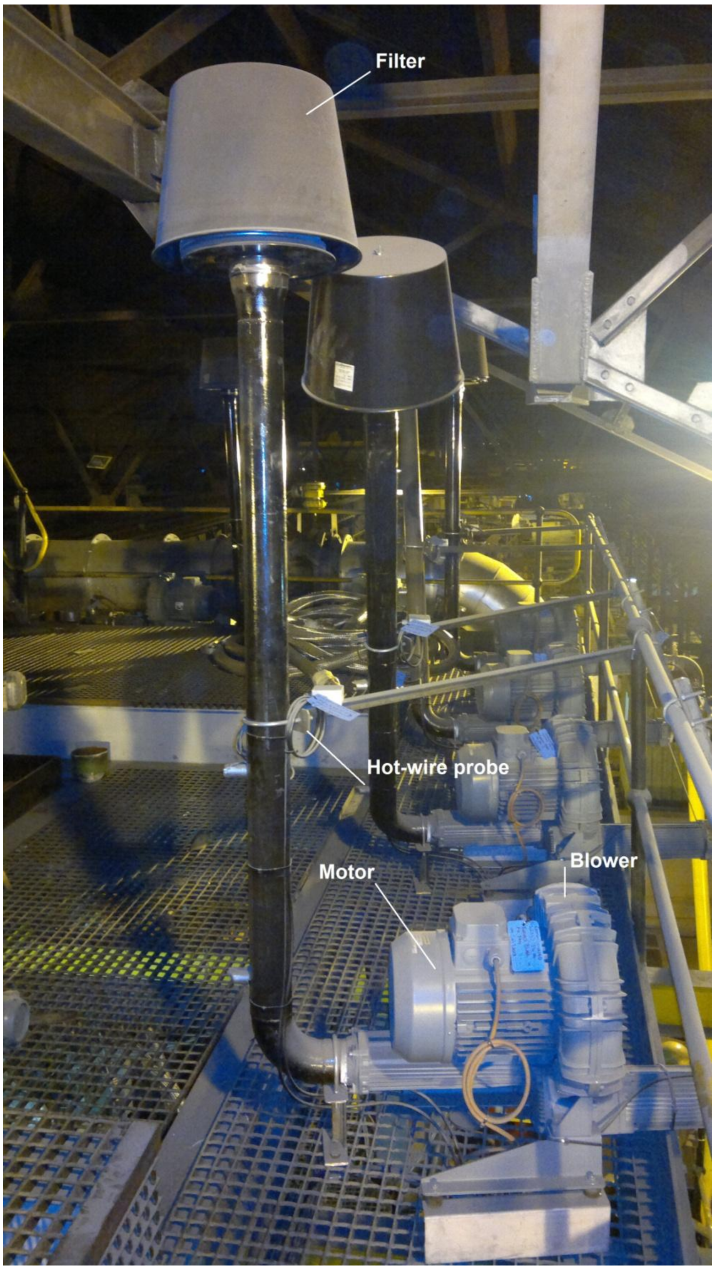

Figure 11: Low-pressure blast air system

5.6 Constant high-temperature cooling water

The water-cooling system in the Rivet plant differed significantly from the system implemented in Letaba. For Rivet open-circuit cooling towers were employed. The water circulated through the cooling towers (the dirty water circuit) was collected in a concrete sump and circulated through plate-type heat exchangers and back to the cooling tower sprayers by centrifugal pumps. On the softened water side (clean water circuit) of the heat exchangers the water was circulated through the furnace and off-gas water circuits by centrifugal pumps and returned to a softened water tank. The system flow diagram is shown in Figure 12.

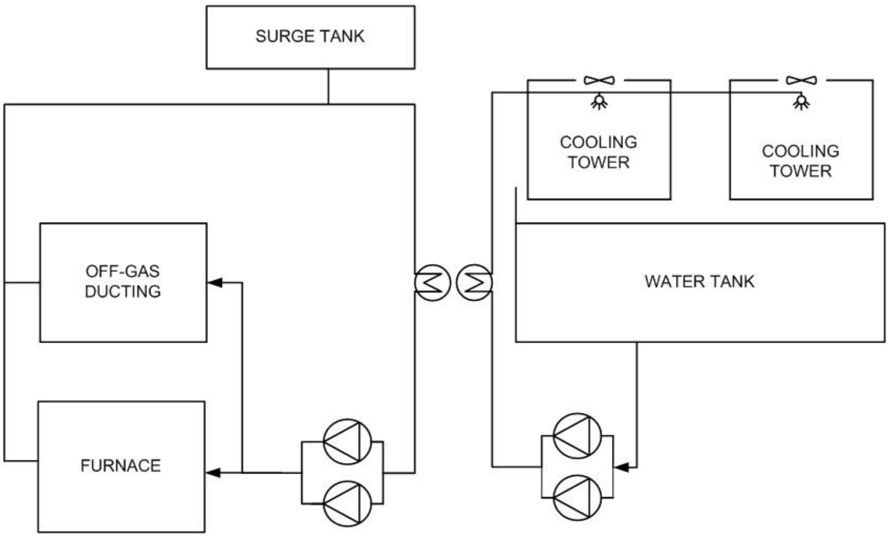

Figure 12: Rivet Cooling water system

For Letaba the complete system was redesigned. Closed circuit cooling towers, two large tanks and new pumps were installed. The dirty water circuits of the towers consist of a sump (part of each tower) and a circulating pump that pumps dirty water to the sprayers. The dirty water passes over coils installed in each tower en route to the sumps – see figure 13.

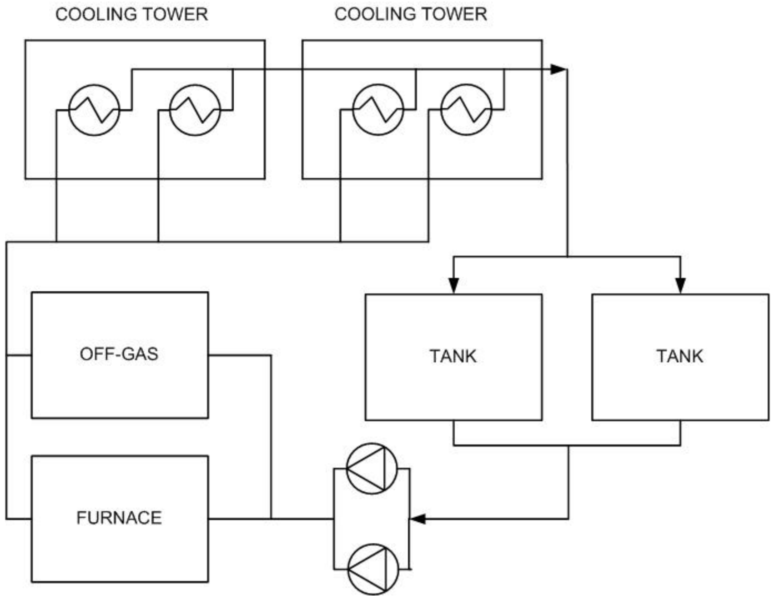

Figure 13: Letaba cooling water system

Softened water (water from which most cations were removed) is stored in two main tanks with a combined capacity of 250 kl. From the tanks two main pumps discharge the water into a common header. From the discharge header a number of circuits are supplied, each fitted with a magnetic flow meter. The heated water is returned through the coils inside the cooling towers and discharged to the tanks. Figure 14 is a picture of the closed circuit towers.

Figure 14: Closed circuit cooling towers

The operating approach of the water-cooling system changed significantly from Rivet to Letaba. With Rivet the approach was to maintain as small a change in temperature across the circuits to be cooled as possible, and run the cooling tower fans at maximum capacity continuously, i.e. run the cooling tower approach at minimum (approximately 4°C above wet bulb) and maintain the airflow at a fixed value. The result was that:

- The temperature of the closed water circuit varied with wet bulb temperature.
- The tower fan power stayed at maximum.
- The water flow rate in the clean water circuit was high to maintain a small change in temperature. The high flow rate caused high specific pumping power.

With Letaba the control approach was changed to a constant, and as high as possible, closed water circuit temperature to the plant and a change in temperature of 10°C across the circuits to be cooled. The constant temperature to the plant was primarily decided on to limit temperature variations in the copper coolers that cool the slag line in the furnace. Due to the high thermal expansion coefficient of copper can cause the coolers to lose contact with refractory bricks or exert unwanted forces on the bricks with temperature changes. The high-ΔT across the circuits to be cooled was selected to reduce flow and thus pump power.

The result was:

- The tower capacity substantially increased as the water temperature into the plant increased – current practice is to maintain this between 40°C and 45°C.
- The electrical use of the water plant as a ratio of electrical power to heat rejection reduced.

Flow and power values for the two systems are given in **Error! Reference source not found.** below.

Table 7: Flow and power values

Parameter	Rivet	LP1
Flow	80 kg/s	180 kg/s
Clean water circulation pump power	75 kW	150 kW
Dirty water circulation pump power	35 kW	15 kW
Fan power (average)	24 kW	60 kW
Total electrical power	134 kW	225 kW
Average water temperature	18°C (estimated)	40°C
Average heat load	1.5 MJ/s	6 MJ/s

Parameter	Rivet	LP1
Specific electrical power/(heat load)	89 kW/(MJ/s)	37.5 kW/(MJ/s)

The resultant saving in electricity due to the Letaba water-cooling strategy is 309 kW. This was calculated as follows: Heat load for Rivet = 1.5 MJ/s, power to thermal load 89 kW/(MJ/s). At the same heat load as Letaba (6 MJ/s) the Rivet water plant would have required 89 x 6 = 543 kW power, Letaba uses 225 kW, or 309 kW less than the Rivet design extrapolated.

5.7 Conclusion

In this chapter the predicted change in energy efficiency of Letaba was shown and evaluated. The results from the conceptual design were discussed and both hypotheses evaluated. The energy efficiency was significantly improved. Measurement and verification was discussed. Two energy efficiency measures that were implemented were described and their results presented in sections 5.6 and 5.7.

CHAPTER 6

In Chapter 6 five alternative commercial plant configurations are presented and their energy efficiency and cost are predicted. Recommendations are made regarding further research.

Ideals are like stars; you will not succeed in touching them with your hands. But like the seafaring man on the desert of waters, you choose them as your guides, and following them you will reach your destiny.
~Carl Schurz, address, Faneuil Hall, Boston, 1859

6 Conclusion and recommendations

6.1 Overview

Five alternative FCP configurations are discussed briefly in this chapter:

- FCP1 is similar to LP2, except that the inductor and furnace bottom water-cooling are replaced with thermal oil-cooling and more solar thermal energy is captured.
- FCP2 is identical to FCP1, except that all electricity is internally generated by combusting additional coal as is oxygen.
- FCP3, FCP4 and FCP5 are also coal-fired off-grid configurations with oxygen self-generation, but with a gas turbine top and ORC bottom cycle.
    - In FCP3 an EFGT is installed as a top cycle.
    - In FCP4 coal is gasified and syngas combusted in an integrated flue gas treatment (IFGT) top cycle.
    - FCP5 has a coal-fired IFGT and EFGT utilizing off-gas thermal energy as the top cycle.

The final FCP configuration will depend on technology development over the next ten years. In view of this future research needs are identified and recommendations are made.

6.2 Implication for full commercial plant

The study has indicated measures that can be considered to increase the energy efficiency of the existing AlloyStream demonstration plant. The measures are applicable to a future commercial plant but the following key differences between Scenarios 1 and Scenario 2 must be considered:

- A commercial plant will feature substantially larger furnace/s.
- Larger furnace/s will probably not require fuel gas during normal operation, as sufficient combustion energy will be generated by carbon monoxide gas from the heaps.
- The electricity tariff structure will probably consist of a demand and an energy component. Letaba electricity tariff is a fixed rate energy charge. An operating SAF-based plant in the Mpumalanga province is billed (2013) an effective 70 c/kWh [84]. The implication is that the payback period of ECMs as calculated in this study will increase by 40%.
- Self-generation of oxygen will be required.

- ECM technology development will result in improvement in performance and reduction in cost. In this regard the following improvements are predicted:
    - The cost of VSDs will reduce.
    - With proper selection it will be possible to oil-cool the inductor coil, adding 2 640 kJ/s thermal energy to the thermal oil circuit of FCP.
    - Solar PV efficiency will continue to improve. The capex cost of solar PV and solar thermal will reduce.
    - The capital cost of ORC, KRC and SC will reduce.
    - Gas turbine technology with IAC, water injection (WI) and STIG will reach maturity. The capex cost of gas turbines will reduce and the efficiency will improve.
    - High-temperature gas movers will enable off-gas recirculation.
    - Coal gasification technology will mature and reduce in cost.
    - VPSA or membrane technology will reduce the electricity required to generate oxygen.
    - The upper working limit of high-temperature high-efficiency gas filters will move from the current 850°C to 1 000°C offered by MikroPul and Theisen [118, 119].
    - The cost of high-temperature materials such as Kanthal, refractory metals and ceramic linings will reduce and the availability of the materials will increase.

In the light of the above predictions five conceptual designs of a first commercial plant were developed: FCP1 to FCP5. FCP1 is a scale-up from LP2 with furnace bottom and inductor-cooling with thermal oil added. All five FCP configurations are based on Scenario 2.

The scale-up effect from LP2 is common across the five conceptual commercial plant configurations. Scale-up reduces the specific energy use of non-furnace systems such as raw material handling, lights, other auxiliaries and water-cooling systems as well as the heat transferred through the furnace walls. The electrical power required to drive the related electrical loads is predicted to rise by four times even though the product output increases by ten times.

The heat loss through the furnace roof and bottom increases linearly with an increase in reaction area and at heat loss through the sidewall with the square root of the reaction area, assuming that the FCP furnace geometry is the same as LP1 and LP2. Since the area of the roof and bottom is about 50% of the total area the increase in heat loss is 6.5:1 for ten-fold process area increase.

It is predicted that the production of carbon monoxide gas in a large furnace will meet or exceed the energy requirement of the process; therefore no fuel gas will be required. For FCP it is assumed that no excess carbon monoxide will exit the furnace. The implication is that only latent heat will be recovered from the off-gas, as is the case with LP2. In addition, solar energy will be captured with a solar thermal system and collected with thermal oil. The area collecting solar energy is increased by a factor of 2. Energy storage is achieved with a large reservoir of thermal oil. Oxygen is generated with VPSA or membrane technology at 1 500 kJ/kg. ORC, KRC or SC engines perform the bottom cycle function.

Apart from the above, FCP1 differs from LP2 in that the waste heat from the inductor and bottom cooling is transferred to thermal oil and oxygen is generated by an external OP that is powered from the national grid. A basic energy flow diagram for FCP1 is shown in **Error! Reference source not found.**.

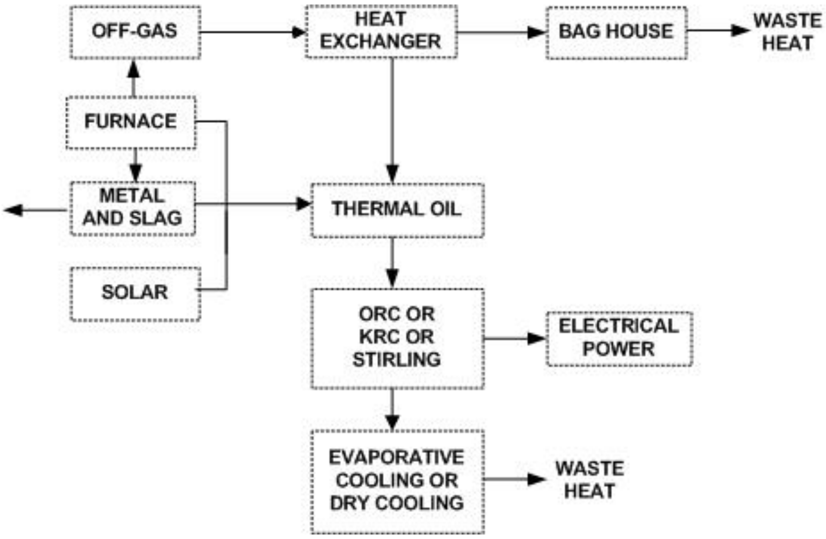

Figure 15: FCP1 basic energy flow diagram

FCP2 is identical to FCP1 except that additional coal is combusted in the plant to meet the plant electrical requirements and oxygen is generated internal to the plant, as is the case with FCP3, FCP4 and FCP5. This is shown in the simplified energy flow diagram **Error! Reference source not found.**.

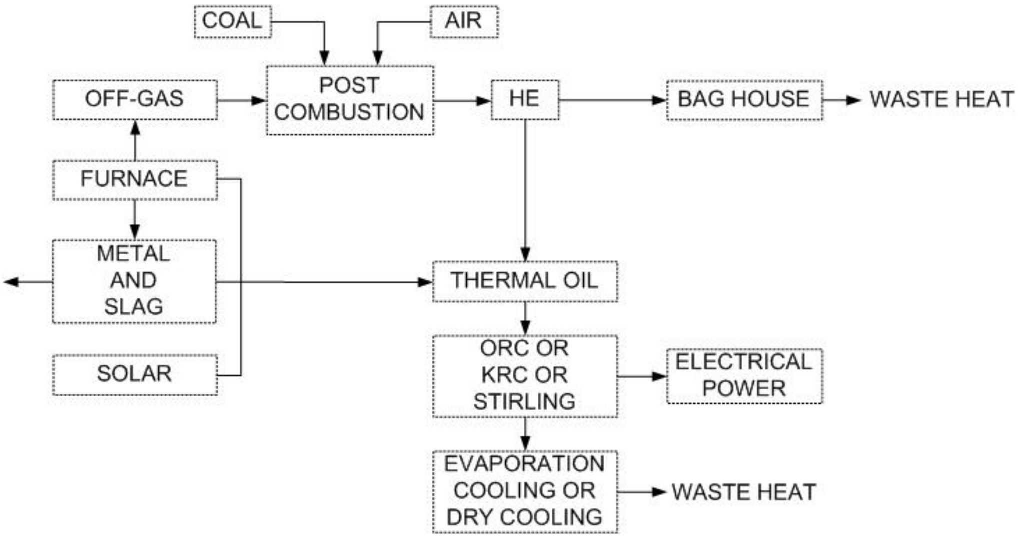

Figure 16: FCP2 basic energy flow diagram

FCP3 also burns additional coal, but a combined cycle is employed to convert thermal energy to electricity. Additional coal and oxygen is combusted in the off-gas before the EFGT heat exchanger. The increased off-gas thermal energy above approximately 200°C is transferred to a low-pressure EFGT with a turbine inlet temperature of 1 000°C. The EFGT is equipped with IAC, WI and STIG. Waste heat from the EFGT is passed to the thermal oil system at 300°C. See **Error! Reference source not found.**.

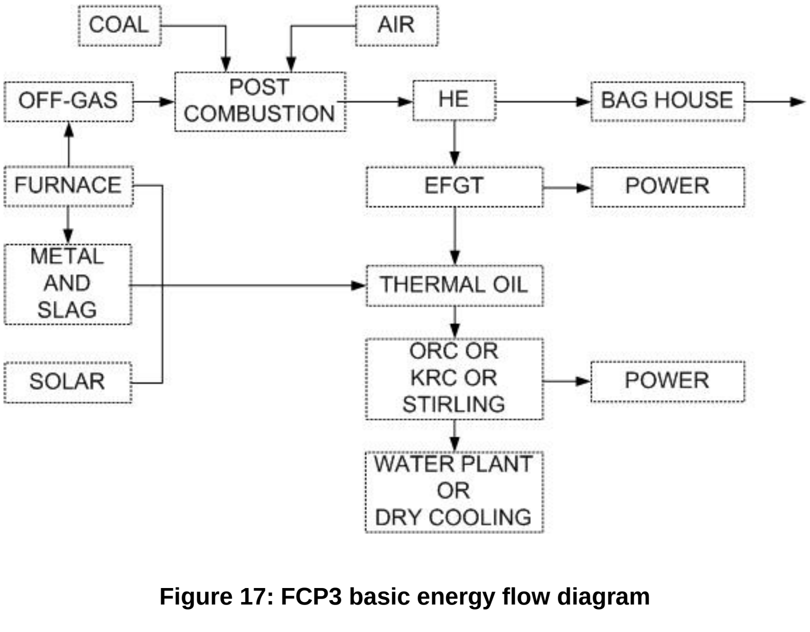

Figure 17: FCP3 basic energy flow diagram

FCP4 is the same as FCP3 except that an IFGT fuelled by syngas is used as a top cycle instead of the EFGT of FCP3. Off-gas heat is passed to the bottom cycle through a heat exchanger. The gasification system is supplied with oxygen, coal and water. The generated syngas is scrubbed and supplied to a high-efficiency gas turbine or turbines. The gasification efficiency is 80% and turbine efficiency 35%. See **Error! Reference source not found.**.

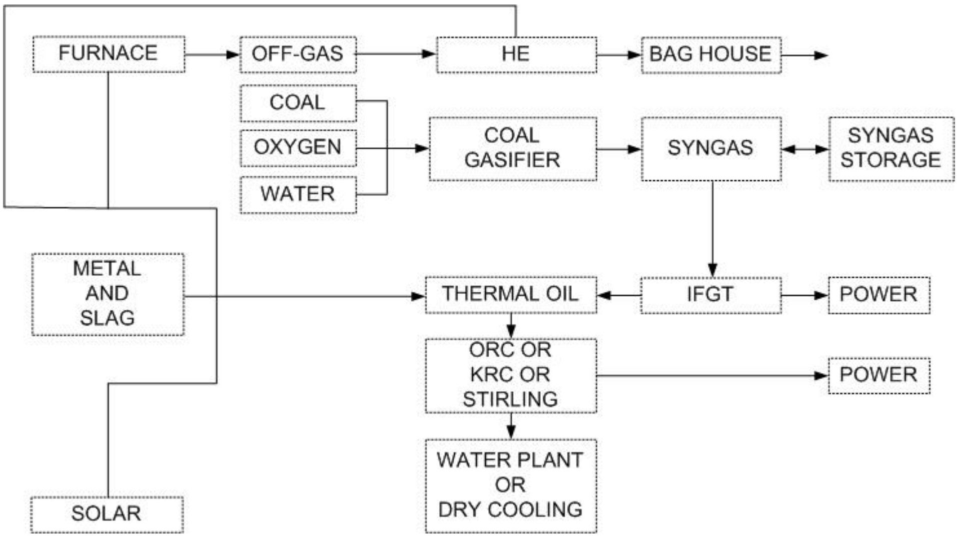

Figure 18: FCP4 basic energy flow diagram

FCP5 is the same as FCP3, except that an IFGT with the additional coal directly injected is added. A high-temperature filter cleans the gas stream after the coal combustor. See **Error! Reference source not found.**.

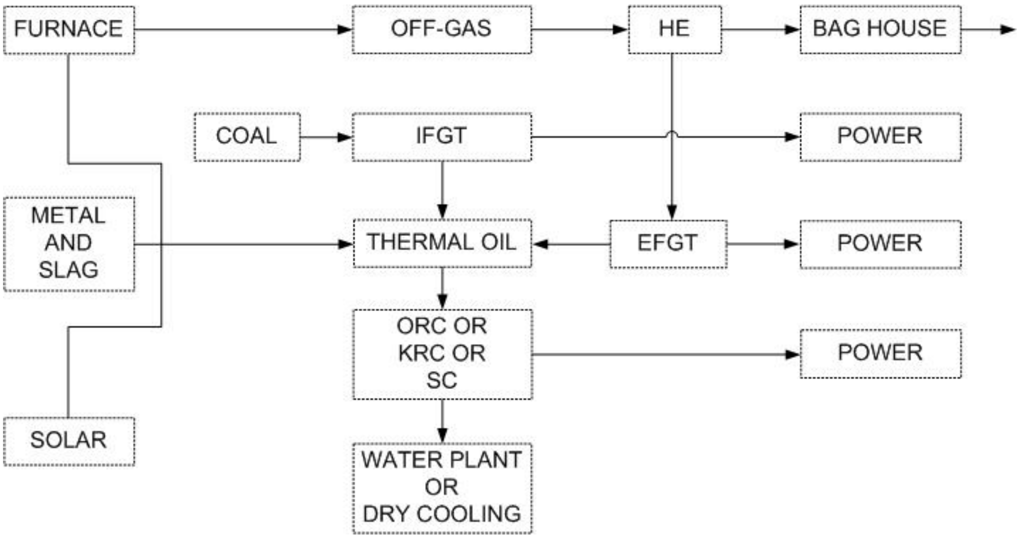

Figure 19: FCP5 basic energy flow diagram

The projected efficiencies are shown in **Error! Reference source not found.**. The energy efficiencies are based on efficiencies G2GEE1, G2GEE2 and S2GEE. G2GEE1 is calculated by dividing the metal enthalpy with the sum of coal and fuel gas (and electrical energy in the case of FCP1) entering the plant. G2GEE2 is calculated by dividing the metal enthalpy with the input energy of G2GEE1 with solar energy added. S2GEE is calculated by adding all the energies from source to plant, including the coal burn at the CFPP to supply the OP with power, and using this value as the input energy divided into the metal enthalpy. For LP1, LP2 and FCP1 some of the coal is used by the CFPP to generate electricity for the plant and oxygen supplier. FCP2, FCP3, FCP4 and FCP5 burn coal to be self-generating (off-grid) plants and oxygen is generated internally. The highest G2GEE1 and G2GEE2values are achieved in FCP1, primarily because of the high coal-to-electricity efficiency (37.5%) achieved in the CFPP. It is also the least complex commercial plant configuration. Capex estimates for the various FCP configurations were not attempted.

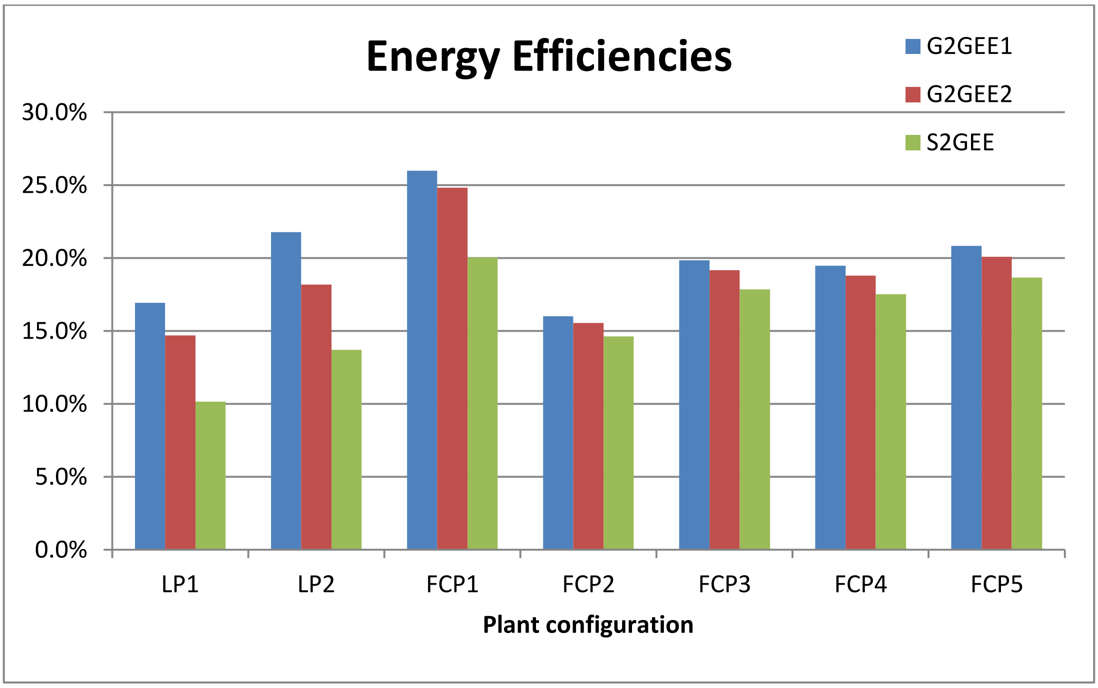

Figure 20: Energy efficiencies of the various plant configurations

Energy and transport are two key cost elements of an AlloyStream plant. The costs of the two elements, as well as water cost, are shown in **Error! Reference source not found.**. To minimise transport cost FCP is located next to the ore resource. Coal is trucked from a mine 720 km away. The transport cost for the commercial plant is significantly less than for the prototype facility, even though the unit transport cost (R1.25/km.ton) and total distance that ore and coal are transported is the same. This illustrates the importance of optimum location and hence the need for electrical self-sufficiency.

Although relatively insignificant, there is a marked increase in water cost due to self-generation with evaporative cooling. Dry-cooling can be employed but it will adversely affect the capex and bottom cycle efficiency. The estimated reduction in bottom cycle efficiency due to dry-cooling is 2%.

Error! Reference source not found. also shows the opex benefit of waste heat recovery and self-generation. The energy cost is based on an effective grid power cost of 70c/kWh for FCP1. Additional coal is combusted to replace grid power for the other FCP configurations. No maintenance or capital cost is included.

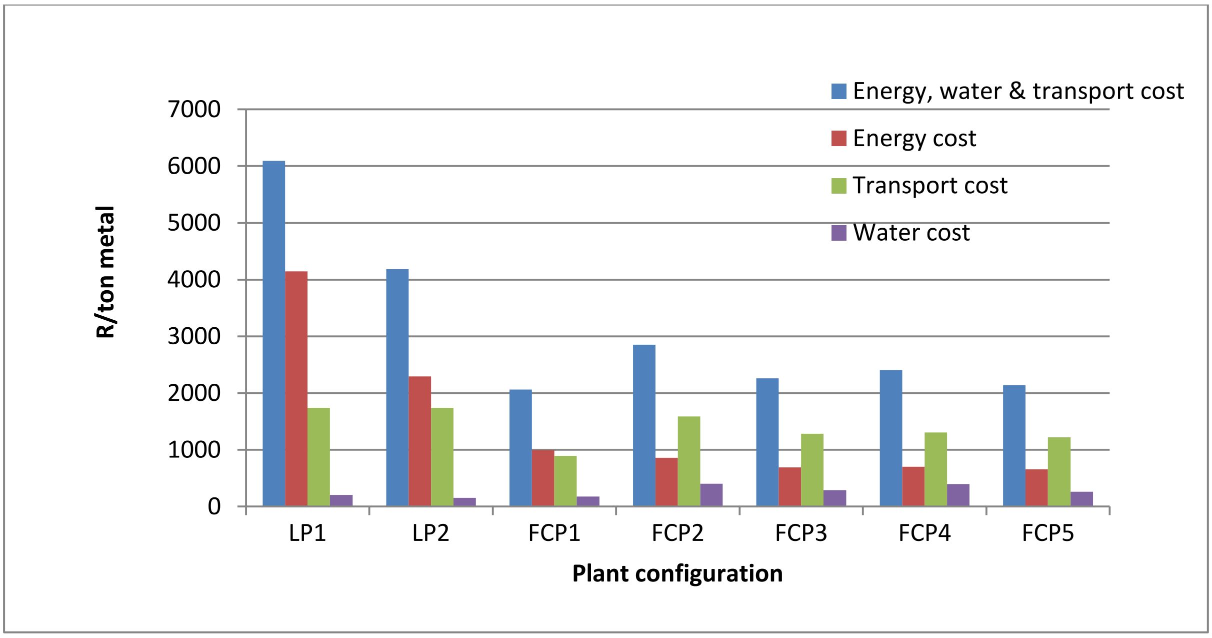

Figure 21: Key cost elements, 2013 base, evaporative cooling

6.3 Further research

It is clear that a gas turbine, either in EFGT or IFGT guise, is likely to feature in a future plant. IAC has merit, considering the anticipated placement of the plant in a hot and high location. Commercial solutions are available to inject water into the inlet air stream before it enters the compressor [120]. By injecting water into the inlet air stream the compressor inlet temperature can approach wet bulb temperature. This results in a reduction in compressor work and a reduced temperature after compression [121]. A lower temperature after compression will enable an increase in heat recovery from the off-gas stream, relevant to

FCP3 and FCP5. The overall result is an increase in heat recovered with a marginal increase in thermal efficiency – therefore an increase in overall efficiency and work output by the gas turbine. Limited STIG can also improve the efficiency of the cycle and the power output and increase the life of the gas turbine [122].

Giampaolo [122] quotes the following figures from General Electric for IAC: at a dry bulb temperature of 27°C and relative humidity = 20%. IAC will reduce the heat rate by 1.5% and increase the power output by 8% through fogging. This is confirmed by Meher-Homji and Mee [121].

The total work that can be generated from a hot gas stream such as off-gas by a combined cycle is primarily dependent on the following factors:

- The ΔT between the working fluid of the EFGT entering the heat exchanger and the off-gas exiting the heat exchanger (the pinch point).
- The EFGT's compression ratio and turbine inlet temperature.
- The EFGT's compressor and turbine efficiencies.
- The load on the EFGT.
- The air inlet temperature to the compressor.
- The ΔT between the EFGT's working fluid at turbine outlet and the bottom cycle's maximum cycle temperature.
- The temperature at which the bottom cycle rejects heat to the atmosphere.

The temperature difference across the off-gas to EFGT heat exchanger was assumed as 160°C, in order to compensate for fouling by dust carried over from the furnace to the off-gas. Mechanical scrapers could be considered to reduce fouling and hence increase cycle efficiency.

Coal gas was discovered in the late 18th century. Since then the conversion of coal and biomass to a gas has been studied, developed and applied widely. After the 1973 oil crisis the US Department of Energy funded coal gasification research with the objective of reducing the USA's dependence on imported oil. The technology has advanced to the point that an electricity generating plant based on a combined cycle fuelled with syngas from coal is a viable alternative to a coal-fired plant. More than five gasification technologies are deemed commercially available by Phillips, ranging from high-pressure to low-pressure syngas reactors. Another four are viewed as nearly commercially ready [123]. Typical coal-to-syngas energy conversion efficiency ranging from 65% to 80% is claimed. The syngas LHV is between 4 000 kJ/kg to 12 000 kJ/kg. The International Energy Agency Clean Coal

Centre lists seven commercial gasification technologies that are commercially available and three as under development [124].

Oxygen is produced almost exclusively by air liquification or VPSA. Using air liquification 98% + pure oxygen is produced. Commercial VPSA plants are configured to deliver similar purities [114]. The AlloyStream^{TM} process, however, requires oxygen-enriched air in the range of 25% to a maximum of 60% by mass. This requirement could be met by a VPSA system at a lower specific energy than the typical 1 980 kJ/kg (0.55 kWh/kg) for air liquefaction or high purity VPSA plants [125]. In addition, membrane technology has recently entered the market. This technology is claimed to substantially reduce the specific power required to generate the oxygen-enriched air [50].

The heat transfer that occurs inside the furnace vessel was excluded from this study. However, the energy efficiency of the process inside the furnace has a very significant impact on the overall plant energy efficiency. The process energy requirement of 2 174 kWh/ton metal is a sum of the following:

1. Heating of the ore, reductant and blast gases
2. The net energy required by the various reduction reactions
3. Changing the metal and slag phase from solid to liquid
4. Heating the metal and slag to 1 550°C

To achieve the 2 174 kWh/ton process energy in the order of 10 000 kWh/ton chemical and electrical energy is supplied to the vessel. About 4 000 kWh/ton exits the vessel as thermal energy in the off-gas stream and the balance of 3 500 kWh/ton exits through the walls as heat loss. Only a partial reduction in heat loss and a relatively insignificant amount of heat regeneration was addressed in this document. In theory it is possible to replace the nitrogen entering the furnace (80% of blast air) with off-gas recirculation. If this can be done practically, the oxygen quantity needed to generate the required 1 550°C could be significantly less than used in the model, and the energy efficiency of the furnace could increase substantially. However, less thermal energy will be available to generate electricity, so even though the energy efficiency will increase, the total cost of energy may increase, as will the complexity of the plant. Off-gas recirculation will require a high-temperature gas moving system that can pump in the order of 10 kg/s off-gas at a pressure of 3 000 Pa above ambient.

An alternate approach is to accept the current furnace inefficiencies and utilise the waste heat to reduce the total cost of energy, as was done for LP2. FCP takes this one step further by using self-generation. This approach is feasible and may even be imperative to the deployment of the technology. Since the process is reliant on coal as a reductant, coal material storage and handling systems are already present. The furnace can also be viewed as a heat generator and the off-gas system already has heat exchangers and gas filtering. In addition, heat conversion to electricity is proposed in this study, so to expand the systems to burn additional coal and thereby make the plant independent of external electrical power is a logical progression.

The LP2 conceptual design is based on evaporative water-cooling. In practice at Pretoria the average wet bulb temperature is 15°C to 17°C and a heat rejection temperature for the bottoming cycle of wet bulb +5°C, or 20°C to 22°C is achievable. This should be similar in a Hotazel location where a lower relative humidity is expected. If no water consumption is a requirement dry-cooling will have to be employed, using fin fan coolers. Dry-cooling has two disadvantages – the fan power is significantly more than the fan power for cooling towers, and the heat rejection temperature is at dry bulb +20°C. The elevated heat rejection temperature of dry-cooling reduces the thermal efficiency of the bottoming cycle by an estimated 2%.

The generation of a margin of excess power could play an important role. By cooling down a large thermal mass at night (a water or thermal oil reservoir), the high ambient in daytime can be countered. The mix of energy available for generation and storage will have to be managed continuously to maintain an optimum daily efficiency.

Electrical capacity reserve and internal network stability is a factor that will require careful attention in self-generation. Internal network design falls outside the scope of this study.

6.4 Recommendations

An important aspect of the ECM Evaluation Matrix (Appendix B) is the confidence rating. A low rating indicates a lack of dependable information, either because it could not be found or it does not exist. In practice there are three actions that can be taken to increase the confidence in the measure:

- Search for literature, visit appropriate sites, contact experts
- Run a small-scale test
- Run a full system

Letaba offers a unique opportunity to test on small- or full-scale.

This study has focused on one aspect of energy management, namely engineering improvements, and has ignored energy management and demand management due to the flat rate charged. During the design, energy efficiency should be one of the criteria used to evaluate solutions. Once the plant is in operation, energy management should be practiced, the US EPA Energy Star program could be an excellent starting point leading to ISO 50001 certification. All significant energy usage should be measured and recorded and adjustments to the operations made to hold the efficiency gains and even improve on them.

In addition to energy management the following development initiatives are recommended:

- Do full-scale research and testing on an EFGT with IAC and water injection and STIG.
- Do full-scale research and testing on coal gasification to IFGT system.
- Build a small high-temperature off-gas-to-air heat exchanger and install it in the off-gas system of Letaba as near to the furnace as possible. Experiment with anti-fouling solutions.
- Install a small ORC with an oil circuit to harvest heat from the second stage off-gas duct on LP1.
- Develop the energy model that supported this study to include various operating regimes, and include energy storage and demand management.
- Develop a model for self-generation of electricity based on coal as a fuel source for an EFGT with IAC and STIG, or coal gasification integrated with off-gas and syngas powered IFGT with IAC and STIG.
- Develop and test a coal-fired IFGT micro-turbine with high-temperature filters.
- Test membrane filter technology on a pilot basis to generate oxygen-enriched air.

6.5 Conclusion

This study was initiated by a need to improve the energy efficiency of a prototype ore reduction plant. By following the research methodology valuable results were obtained, pointing the way for plants that may be built in the future. The study could also be of value to existing plants in industry, as the ECMs studied can in most cases be retrofitted to existing plants.

The study proved that the energy efficiency of the as-built Letaba plant can be significantly improved and the energy cost to the plant substantially reduced. When extrapolated to a commercial size plant even better results are predicted. Further research and development is recommended to increase confidence in the predictions and accelerate the commercialisation of promising technology.

The road to this document took the author through a number of stages. The first was a growing realisation that energy efficiency is critical to the success of the AlloyStream^{TM} technology and that it was not high on the development agenda. Stage 1 took about three years. This realisation increased the awareness of the author of how energy was used in the plant.

In Stage 2 a burst of discussions and reading of information on energy recovery methods followed. This lasted about two years. During Stage 2 Letaba was designed and the constant temperature water-cooling system implemented. A fork in the road appeared after Stage 2 – should the investigation into improved energy efficiency be a commercial investigation only, or should it also be subjected to the rigours of academic scrutiny? The latter was chosen primarily for the quality assurance inherent in the scientific method.

The start of Stage 3 was the research proposal, followed by mostly a muddle in the dark for eighteen months. At the start of Stage 4 the writer had accumulated a large amount of information and the work of sifting through it, structuring the dissertation, reading and thinking and again reading had started. All along something profound was happening almost unnoticed. Clarity and purpose replaced opinions, guesses and confusion. And energy efficiency became a priority on the development agenda of the business.

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Appendix A: System utility functions

Table 8: Safety criterion table

Criterion = Safety, Weight = 8	
Rating	
Barely acceptable: 1 or 2	System failure probability very high (1 or 2)
	Very high probability that the failure will harm people in the immediate vicinity (1 or 2)
	People are always in the immediate vicinity of the system (1 or 2)
Below average: 3 or 4	System failure probability high (3 or 4)
	High probability that the failure will harm people in immediate vicinity (3 or 4)
	People are in the immediate vicinity of the system most of the time (3 or 4)
Average: 5 or 6	System failure probability average (5 or 6)
	Average probability that the failure will harm people in immediate vicinity (5 or 6)
	People are sometimes in the immediate vicinity of the system (5 or 6)
Above average: 7 or 8	System failure probability low (7 or 8)
	Low probability that the failure will harm people in immediate vicinity (7 or 8)
	People are seldom in the immediate vicinity of the system (7 or 8)
Exceptional: 9 or 10	System failure probability very low (9 or 10)
	Very low probability that the failure will harm people in immediate vicinity (9 or 10)
	People are almost never in the immediate vicinity of the system (9 or 10)

Table 9: Financial criterion table

Criterion = Financial, Weight = 6	
Rating	
Barely acceptable: 1 or 2	15 to 20 years payback
Below average: 3 or 4	10 to 15 years payback
Average: 5 or 6	5 to 10 years payback
Above average: 7 or 8	2 to 5 years payback
Exceptional: 9 or 10	Less than 2 years payback

Table 10: Reliability criterion table

Criterion = Reliability, Weight = 5	
Rating	
Barely acceptable: 1 or 2	The ECM is much more complex (has many additional interfaces) than the baseline system configuration and is less reliable than the system it replaces. The replaced system is no longer functional.
Below average: 3 or 4	The ECM is somewhat more complex than the system it replaces and the replaced system is no longer functional.
Average: 5 or 6	The ECM is as complex than the system it replaces and the replaced system is no longer functional.
Above average: 7 or 8	The ECM is more complex than the system it replaces and the replaced system is functional as a standby.
Exceptional: 9 or 10	The ECM is as (or less) complex than the system it replaces and the replaced system is functional as a standby.

Table 11: Social criterion table

Criterion = Social, Weight = 1	
Rating	
Barely acceptable: 1 or 2	No local job creation, no environmentally responsible marketing value (except for a small reduction in externally supplied energy) and high likelihood of significant pollution, no reduction in consumption of water.
Below average: 3 or 4	No local job creation, no environmentally responsible marketing value (except for a small reduction in externally supplied energy), insignificant reduction in consumption of water, medium likelihood of significant pollution.
Average: 5 or 6	Minor local job creation, no environmentally responsible marketing value, small reduction in the consumption of water, medium likelihood of significant pollution.
Above average: 7 or 8	Significant local job creation, significant environmentally responsible marketing value, significant decrease in consumption of water, low likelihood of significant pollution.
Exceptional: 9 or 10	Substantial local job creation, high environmentally responsible marketing value, substantial decrease in consumption of water, no likelihood of significant pollution.

Appendix B: Complete evaluation matrix

Potential energy conservation measures																				
		Safety				Financial				Reliability				Social				Totals		
	Weight →	8				6				5				1						
ECM no.		R	C	U	D	R	C	U	D	R	C	U	D	R	C	U	D	C	U	D
1	Replace IE1 electrical motors with IE3	10	0.9	80	72.0	7	0.9	42	37.8	8	0.9	40	36.0	4	0.5	4	2.0	0.8	166	148
2	Upgrade inductor	8	0.9	64	57.6	6	0.5	36	18.0	5	0.9	25	22.5	5	0.5	5	2.5	0.7	130	101
3	Natural solar lighting	7	0.9	56	50.4	7	0.9	42	37.8	9	0.9	45	40.5	7	0.9	7	6.3	0.9	150	135
4	Convert solar radiation to electricity	9	0.9	72	64.8	1	0.9	6	5.4	8	0.5	40	20.0	9	0.5	9	4.5	0.7	127	95
5a	Install VSDs on all drives above 3 kW	10	0.9	80	72.0	9	0.9	54	48.6	7	0.5	35	17.5	5	0.5	5	2.5	0.7	174	141
5b	Low-pressure blower system	8	0.9	64	57.6	9	0.9	54	48.6	7	0.5	35	17.5	6	0.9	6	5.4	0.8	159	129
6	Upgraded furnace roof refractory	7	0.9	56	50.4	9	0.9	54	48.6	5	0.9	25	22.5	5	0.9	5	4.5	0.9	140	126
7	Thermal oil-cooling	4	0.5	32	16.0	7	0.9	42	37.8	5	0.9	25	22.5	3	0.5	3	1.5	0.7	102	78
8	Ore and coal preheating	5	0.5	40	20.0	2	0.1	12	1.2	3	0.5	15	7.5	4	0.5	4	2.0	0.4	71	31
9	Blast air preheating	4	0.5	32	16.0	7	0.5	42	21.0	7	0.9	35	31.5	5	0.9	6	5.4	0.7	115	74
10	Coal drying with waste heat	4	0.5	32	16.0	6	0.5	36	18.0	5	0.5	25	12.5	4	0.5	4	2.0	0.5	97	49
11a	Off-gas heat recovery with SC	6	0.9	48	43.2	4	0.1	24	2.4	7	0.5	35	17.5	6	0.5	6	3.0	0.5	113	66
11b	Off-gas heat recovery with BC	8	0.9	64	57.6	6	0.5	36	18.0	7	0.5	35	17.5	6	0.5	6	3.0	0.6	141	96
11c	Off-gas heat recovery with SRC	7	0.9	56	50.4	7	0.5	42	21.0	6	0.5	30	15.0	6	0.5	6	3.0	0.6	134	89
11d	Off-gas heat recovery with ORC	8	0.9	64	57.6	6	0.9	36	32.4	7	0.9	35	31.5	6	0.5	6	3.0	0.8	141	125
11e	Off-gas heat recovery with KRC	8	0.9	64	57.6	5	0.9	30	27.0	7	0.9	35	31.5	6	0.5	6	3.0	0.8	135	119
11f	Off-gas heat recovery with BC-ORC	7	0.9	56	50.4	6	0.5	36	18.0	6	0.5	30	15.0	6	0.5	6	3.0	0.6	128	86
12	Waste heat to electricity from metal and slag	5	0.1	40	4.0	5	0.5	30	15.0	4	0.1	20	2.0	7	0.1	7	0.7	0.2	97	22
13	Convert waste heat from ECM 7 to electricity	6	0.5	48	24.0	6	0.5	36	18.0	7	0.5	35	17.5	5	0.5	5	2.5	0.5	124	62
14	Recover pressure energy	6	0.5	48	24.0	3	0.5	18	9.0	7	0.5	35	17.5	5	0.5	5	2.5	0.5	106	53

Legend: R = Rating, C = Confidence, D = Discounted utility (U x C)

Appendix D: Furnace blast gas flows (Campaign 1)

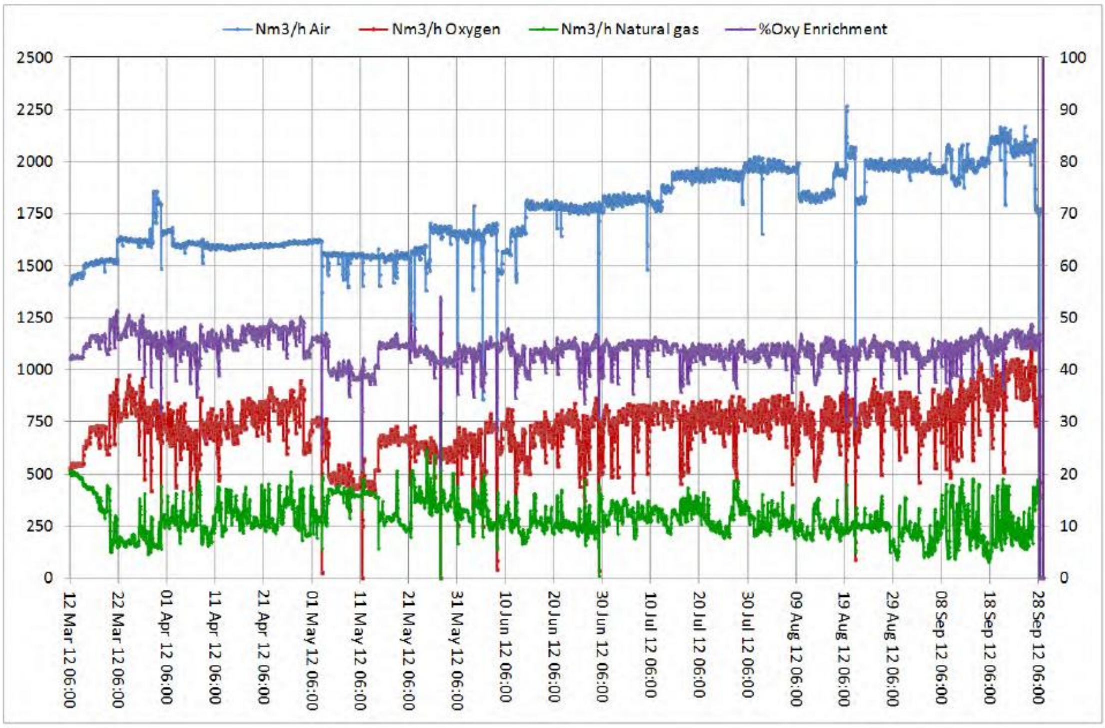


Figure 22: Furnace blast gas flows

Appendix E: Furnace off-gas flow (Campaign 1)

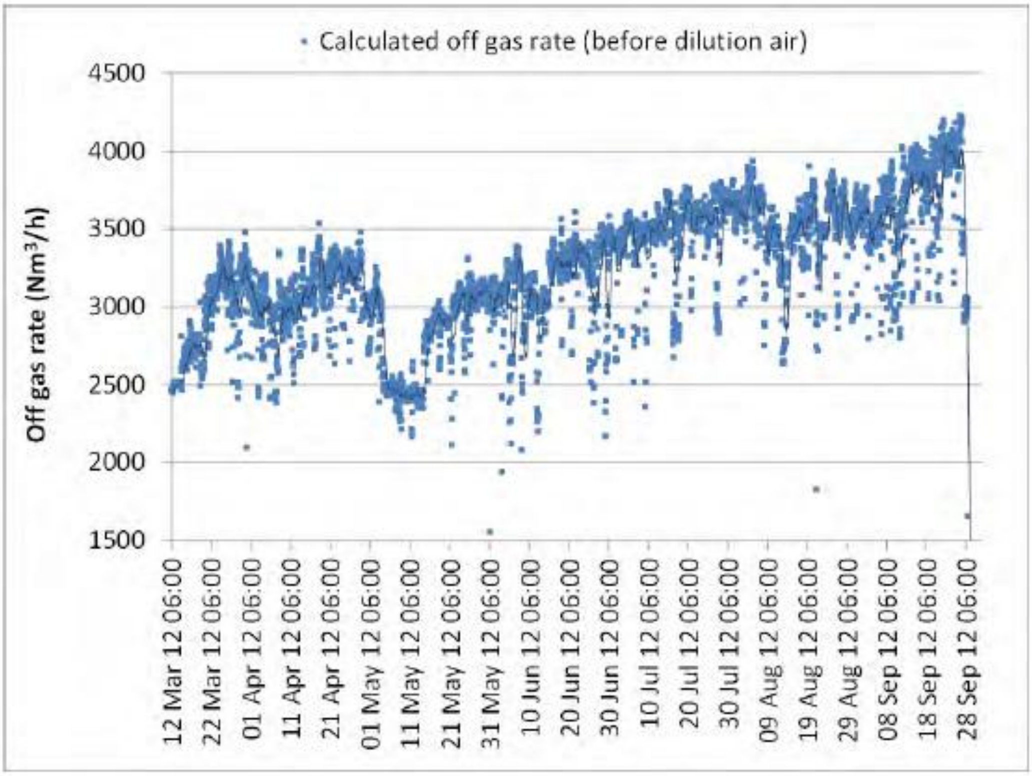


Figure 23: Theoretical calculated wet off-gas volumetric rate

Appendix F: Furnace heat losses (Campaign 1)

Figure 24: Furnace heat losses

Appendix G: Inductor power (Campaign 1)

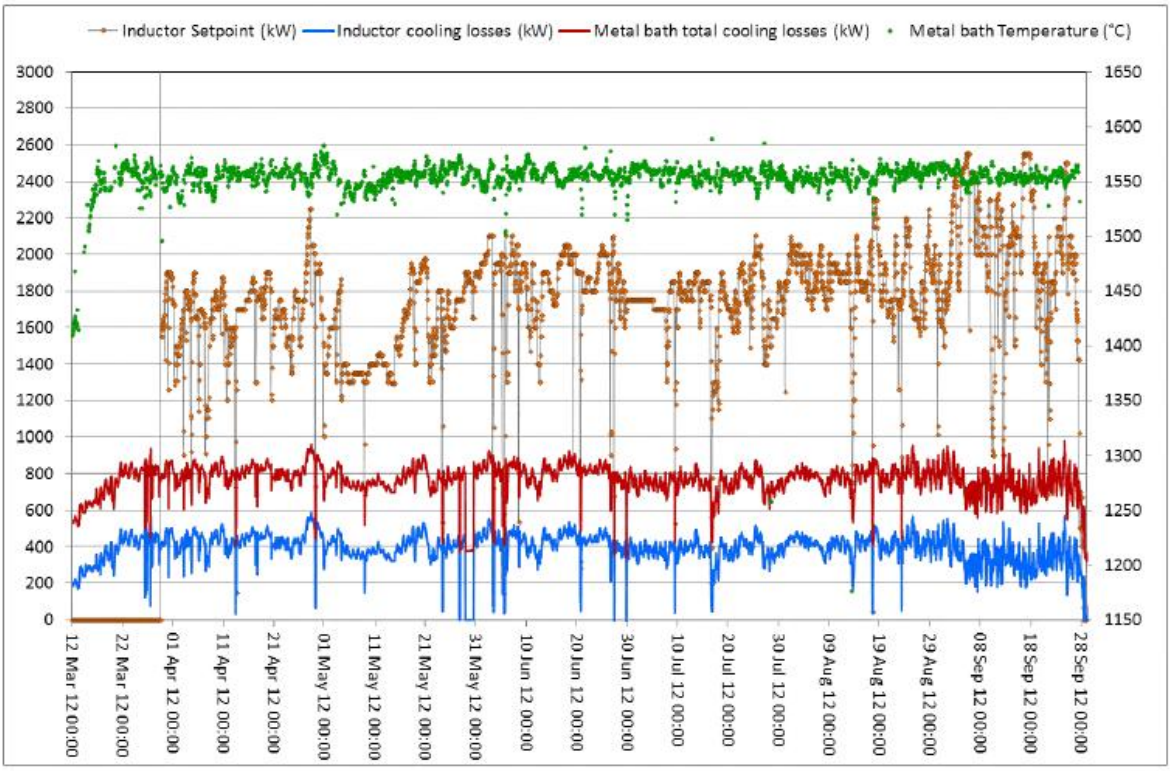


Figure 25: Inductor power for Campaign 1

Appendix H: Compressor calculations

It is assumed the flow rate from the Compair datasheet is based on 15 °C, 100 kPa and a relative humidity of 60%. The rated compressor power is 250 kW at a rated flow rate of 42.7 m^3/min. To simplify the calculations it will be based on dry air and the assumption is made that this will not introduce a significant error. The compressors were operated at 8.5 bar absolute.

Step 1: Calculate T_2, h_1 and h_2 at 15 °C, 100 kPa, 0% relative humidity and a pressure ratio of 8.5

- $T_1 = 288$ K
- $P_1 = 100$ kPa
- $\rho_1 = 1.2$ kg/m^2
- $c_p = 1.005$ kJ/kg
- $\gamma = 1.4$
- $T_2 = 288 \times (8.5)^{0.286} = 531$ K (for isentropic compression)
- Over the temperature range 288 K to 531 K the changes in value for c_p and γ are insignificant
- $h_1 = c_p \times T_1 = 289$ kJ/kg
- $h_2 = 534$ kJ/kg

Step 2: Calculate rated volume and mass flow and approximate efficiency

- $V_{rated} = 42.7/60 = 0.712$ m^3/s
- $\dot{m}_{rated} = 0.712 \times 1.2 = 0.854$ kg/s
- $\eta = (h_2 - h_1)/(250/0.854) = 0.64$

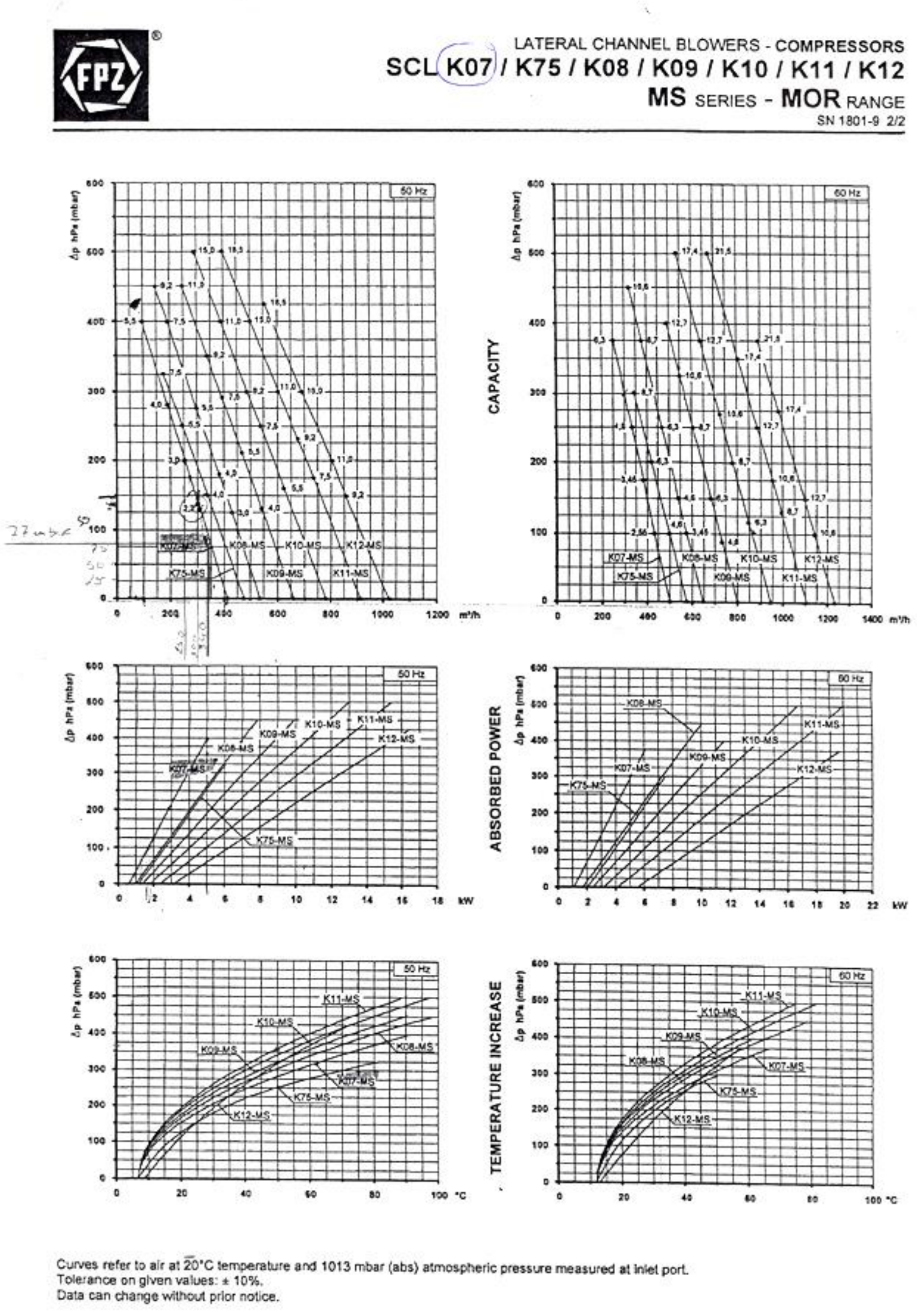
Step 3: Calculate the mass flow required by the plant

- $V_{req} = 2\ 500$ m^3/hour (at 0 °C and 101.325 kPa)
- $\dot{m}_{req} = 1.284 \times 2\ 500/3\ 600 = 0.982$ kg/s

Step 4: Calculate the running power of the two compressors

- Compressor 1 runs at full power 100% of the time and delivers 0.854 kg/s
- Compressor 2 runs on load (0.982 – 0.854)/0.854 = 15% of the time at full power. It idles 85% of the time and draws 250 x (1 - 0.64) = 90 kW
- Total running power = 250 + 0.85 x 90 + 0.15 x 250 = 364 kW

Appendix I: Blower curves



LATERAL CHANNEL BLOWERS - COMPRESSORS
SCL K07 / K75 / K08 / K09 / K10 / K11 / K12
MS SERIES - MOR RANGE
SN 1801-9 2/2

Curves refer to air at 20°C temperature and 1013 mbar (abs) atmospheric pressure measured at inlet port.
Tolerance on given values: ± 10%.
Data can change without prior notice.

Figure 26: Blower curves

Appendix J: Verification of Spreadsheet Calculations

The verification is based on a top down check. The most significant factors are inspected and logic applied to verify the claimed results.

LP1 is taken as the baseline since the values used were obtained from the AlloyStream forward calculator results. The accuracy of the calculations has been confirmed not only through repeated internal checks but also through campaigns 1 and 2.

The key values on which figures 20 and 21 are based are:

Source to gate energy efficiency and the energy, water and transport cost. These will now be examined one by one, starting with the S2GEE.

S2GEE is calculated by dividing the reduction energy rate output from the plant with the total energy rate input to the plant. The reduction energy rate for LP1 and LP2 is identical, as is the reduction energy rate for FCP1 to FCP5 which is 10x the rate for LP1 and LP2.

For LP1 and LP2 the reduction energy is 2 303 kJ/s, calculated by multiplying the reduction energy per ton with the ton per hour, i.e. 2 174 kWh/ton x 1.06 ton/hour = 2 303 kJ/s. For FCP1 to FCP5 this is 23 030 kJ/s.

The total energy rate into the system is dominated by the coal energy rate. For LP1, LP2 and FCP1 no coal is combusted in the plant to generate electricity.

Total energy rate into the system for LP1 is 22 678 kJ/s, for LP2 it is 16 808 kJ/s. The coal mass flow to the plants are identical at 0.31 kg/s. However, since LP2 requires less electricity due to the implementation of the ECMs the coal used by the CFPP for LP1 is 0.36 kg/s compared to 0.20 kg/s for LP2. This represents a difference of about 4 300 kJ/s. Fuel gas use is also significant, for LP1 0.06 kg/s is used, LP2 uses 0.02 kg/s, a difference of 1 483 kJ/s. The remaining difference (406 kJ/s) is from PV solar, turbo-generator and introduction of blowers in place of compressors for blast air.

It seems therefore that the S2GEE for LP1 of 2 303/22 678 = 10.15% and for LP2 2 303/16 808 = 13.7% is reasonable.

LP2 and FCP1 have a similar configuration. FCP1 however requires less system energy per metal ton for the following reasons:

- The coal dryer, raw material handling, inductor power, water cooling plant, forced air cooling and other electrical loads did not increase by the factor 10 that metal output increased with. This contributed to a reduction in coal to the CFPP. The electrical load reduced by 9 616 kW compared to what it would have been if the load of LP2 was increased by a factor of 10 (from 2 768 kW x10 = 27 680 kW for LP2 extrapolated) to 18 064 kW for FCP1). Loads that were not increased by a factor of 10 are shown below.

Load	LP2	FCP1	Comment
Coal dryer	12 kW	48 kW	Scale up efficiency increase load by 400%
Raw material handling and furnace feed	41 kW	166 kW	Scale up efficiency increase load by 400%
Inductor system feed	2 028 kW	13 289 kW	Coil loss increases linearly with diameter, as does side-wall bath losses.
Water cooling plant	183 kW	1225 kW	20% reduction in energy use due to size increase – heat rejected/ton in FCP1 also less than LP1 and LP2 (4 688 kJ/ton vs 3 873 kJ/ton).
Other electrical loads	240 kw	960 kW	Scale up efficiency increase load by 400%.
Oil pump power	62 kW	468 kW	Scale up from LP2 to FCP1 by less than the ratio of thermal energy transported.

- The increase in solar energy due to a plant area increase by a factor of 2 with the added effect of the better conversion efficiency of the ORC further reducing the electricity required from the CFPP by 525 kW.

The combined effect of the above reduces the energy input into the system by 34 734 kJ/s, a reduction in coal use of approximately 1.5 kg/s. This explains the difference between 4.9 kg/s from the coal mine (extrapolated from LP2) and 3.9 kg/s predicted for FCP1.

Having reviewed the difference between LP2 and FCP1, the next step is to review the differences between FCP1 and FCP2, FCP3, FCP4 and FCP5. The metal output of the plants are identical, therefore only the differences in energy input rates will be examined.

Total energy input rate into the system: FCP1 = 114 888 kJ/s; FCP2 = 157 313 kJ/s; FCP3 = 129 029 kJ/s; FCP4 = 131 335 kJ/s; FCP5 = 123 422 kJ/s.

The main reason for the difference in energy rate can be found in the efficiency with which the systems convert the chemical energy from coal to electricity. For FCP1 this conversion is performed by the CFPP at an efficiency of 37.5% minus a 4.61% loss in the grid, or 32.9% of the coal energy entering the CFPP is delivered to the plant as electrical power.

In FCP1 51 279 kJ/s thermal energy enters the ORC and is converted to electrical power at a conversion efficiency of 20%. The ORC thus supplies 10 256 kW gross, or 56% of the plant electrical power. The balance of 7 809 kW is supplied from the CFPP via the grid. The power required internally to pump thermal oil is estimated as 468 kW.

In FCP2 the same amount of thermal (waste) energy enters the ORC from sources other than coal burn, yielding the same result as with FCP1. The shortfall in electricity is 11 346 kW, slightly more than for FCP1 due to the higher water plant heat load requiring an increase in pump power and the power required by the oxygen plant since oxygen generation is internal in FCP2 to FCP5. Based on a combustion efficiency of 90% the overall conversion efficiency (coal to power) is 0.9 x 0.2 = 0.18. Assuming the coal combusted is the same as used in the furnace the coal mass flow to the combustion process is 2.28 kg/s and the heat rejected from the coal burn is 51 686 kJ/s.

For FCP3 the off-gas thermal energy enters the top cycle, not the bottom cycle as with FCP1 and FCP2. This reduces the electrical power from the furnace waste heat stream to 3 978 kW from 10 256 kW for FCP1 and FCP2. The thermal energy from the off-gas combined with the thermal energy from the coal burn results in the combined cycle generating the shortfall of 16 706 kW at an estimated efficiency of 25.1%. The combined cycle efficiency was calculated thus: combustion efficiency (A)= 90%, top cycle efficiency (B)= 25%, heat transfer efficiency from combustion to top cycle (C)=82%, heat transfer efficiency from top cycle to bottom cycle (D)=49%, bottom cycle efficiency (E)=20%. The overall cycle efficiency is A x (C x B + (1 – B) x D x E) = 25.1%. Total thermal energy required is 66 608 kJ/s of which 31 400 kJ/s is from off-gas. 35 208 kJ/s has to be supplied from burning coal giving a coal mass flow of 1.27 kg/s.

For FCP4 it is assumed, as for FCP1 and FCP2 that the off-gas heat enters the bottom cycle. The coal to syngas efficiency is assumed as 80%, the top cycle efficiency is 35%, other efficiencies as for FCP3. The combined cycle efficiency is calculated as 28.1%.

The FCP5 efficiencies are identical to those of FCP3 except for C = 0.91, midway between the value assumed for FCP3 and 1 since there should be no loss in the IFGT but a 0.82 loss for the EFGT. The combined cycle efficiency is calculated as 27.1%.