University of Cape Town

Reducing Industrial Energy Costs through Energy Efficiency Measures in the South African Foundry Industry

- Evaluation and Opportunities of a South African Foundry

Dennis Thiel

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Supervisor: Andrew Hibberd, Energy Research Center

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Abstract

Due to lack of generation capacity and high energy intensities South Africa's electricity supplier is forced to shut down high energy users frequently. Power cuts as well as escalating electricity prices threaten the country's steel industry. The objective of this study was to identify cost-effective energy efficiency improvements for the South African foundry industry. A lack of research in South African foundries was identified as existing literature on the topic was analysed. A large foundry operating an induction furnace in the Western Cape served as subjects to investigate the topic specifically in South Africa. The aim was to identify the energy intensity, evaluate already implemented energy efficiency measures and identify further opportunities to reduce energy cost of the foundry.

The method followed for the data collection was much orientated on an industry energy audit. Types of energy, amounts and cost of energy usage were determined. The energy consumption and energy intensity of the foundry were analysed, based on meter readings, electricity bills and where necessarily a "bottom-up" approach for estimation was used.

Results of the energy audit have shown that the foundry under review consumes about 127,000 MWh annually with a maximum demand of 26,500 kVA. The already implemented energy saving measures decreased the company's energy usage by 5% resulting in a current energy intensity of 1,493ZAR/ton. Further proposed energy efficiency measures included the compressed air system, preheating of the charge material and the reduction of the holding furnaces were analysed. The results of all evaluated measures, namely lighting, load-shifting and maximum demand management were cost effective solutions. Furthermore the recommended energy efficiency measures, namely reduction of compressed air leaks, reduction of holding furnaces as well as preheating of charge material, showed in theoretical calculations a reduction of carbon emissions as well as cost savings.

This study offers an insightful view on energy intensity and energy efficiency opportunities in South African foundries, especially the ones operating an induction furnace.

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Nomenclature

Sym-bol	Description	Unit
R	Resistance	Ω
I	Current	A
P	Power	W
d	Diameter of cylinder (induction furnace)	m
h	Height of cylinder(induction furnace)	m
H	magnetic field intensity	A/m
ρ	Resistivity	Ωm
μ_0	magnetic permeability of vacuum	4π.10-7 H/m
μ_r	relative permeability	H/m
f	Frequency	Hz
C	Coupling factor	
F	Power transmission factor	
Q_{th}	Theoretical energy requirement	MJ or kWh
Q_m	amount of energy required to melt 1t of charge material	MJ or kWh
Q_{sh}	amount to superheat the melt	MJ or kWh
Q_s	heat required to melt slag	MJ or kWh
Q_{en}	energy for endothermic process	MJ or kWh
Q_{ex}	energy for exothermic process	MJ or kWh
M	Mass of charge	kg
c	specific heat capacity of charge	J/kg K
c_m	average heat capacity of molten steel	J/kg K
θ_1	melting temperature of charge	°C
θ_0	initial charge temperature	°C
θ_{sh}	amount of superheat temperature, taken as 50°C	°C
K_s	quantity of slag formed, average 8% of furnace capacity	kg
G_s	heat energy of slag	J/kg K
η	Efficiency	%
Q_a	actual required energy (measured data)	kWh/t
Q_c	heat conduction loss	MJ
Q_R	radiation loss	MJ
ε	Emissivity	
PF	Power Factor	

1. Introduction

1.1. Background

The Republic of South Africa, Africa's biggest economy, is constantly under pressure due to energy supply constraints. Lack of generation capacity and high energy intensities forces the national electricity supplier, Eskom, into shutting down high energy users frequently. The International Monetary Fund (IMF) recently reduced the country's GDP growth outlook for the fourth consecutive time to only 1.4 percent. This represents a non-satisfying growth rate for an emerging economy, especially given high unemployment and poverty issues (Khuzwayo, 2014). The energy crisis is said to remain for at least another three to five years with huge costs for the economy, especially for the industrial sector. According to experts and economists, the power interruptions have cost South Africa's economy about R300 billion and set it back as much as ten percent for potential economic growth (Magwaza, 2014). The electricity supply is at the worst state it has ever been, with situations where up to 40% of the installed generation capacity is not available (Mantshantsha, 2015).

The Steel and Engineering Industries Federation Southern Africa (Seifsa) warns that the electricity disruptions threaten the national manufacturing output. Due to load shedding and electricity disruptions the manufacturing output will be lower than expected in the next years to come (Odendaal, 2015). Due to the generation shortage the Department of Energy has issued an appeal to industry to provide solutions to reduce or possibly shift electricity demand. The government has realized that demand response as well as distributed generation capacity is "critical" to improve the national electricity supply (Creamer, 2015a). South Africa's industry sector is the largest electricity consumer, as shown in Figure 1, and arguably the one suffering most of the electricity disruptions.

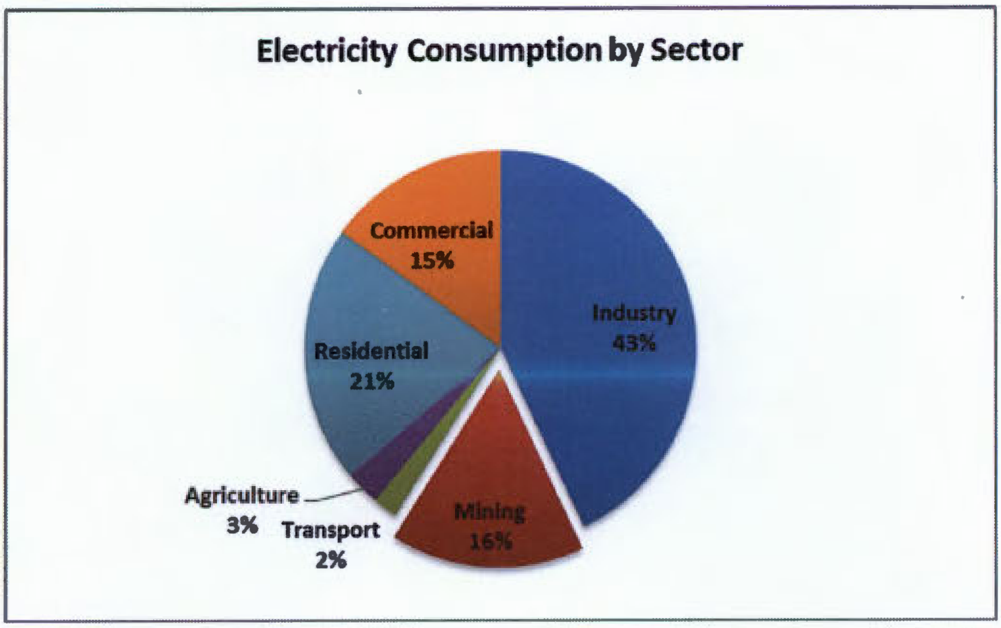

Figure 1: Electricity consumption by sector
(Eskom, 2011)

It is not only power cuts that threaten the industry, but also the escalating electricity prices. Prior to the first power crisis in 2008, the electricity price for industrial users in South Africa has been relatively low in a worldwide comparison. Since the power crisis, and since it became clear that South Africa has underinvested in its generation capacity, electricity consumers have experienced a steep increase in prices. Subsequently the power crisis Eskom implemented demands side management programmes. The company embarked on large-scale capital expansion programmes and adopted a multi-year price mechanism to fund costs. These interventions have had a major impact on electricity prices. The amended implementation of the multiyear price determination resulted in an electricity price increase of 12.69%, while Eskom still requests a further increase of 25.3% (Creamer, 2015b).

Given that South Africa's industry spends about one fifth of their annual expenditure on electricity, as shown in Figure 2, an increase of the electricity price would further threaten the manufacturing output and economy. In the manufacturing industry the three top operating expenses are energy, labour and raw materials. Given these three operating expenses, energy has arguably the highest cost saving potential (Abdelaziz, Saidur & Mekhilef, 2011). The Energy Intensive User Group (EIGU) of South Africa has assessed the cost structure of their members, the most energy intensive production companies in South Africa. As illustrated in Figure 2, electricity is a major component of their cost structure and evidently an increasing part.

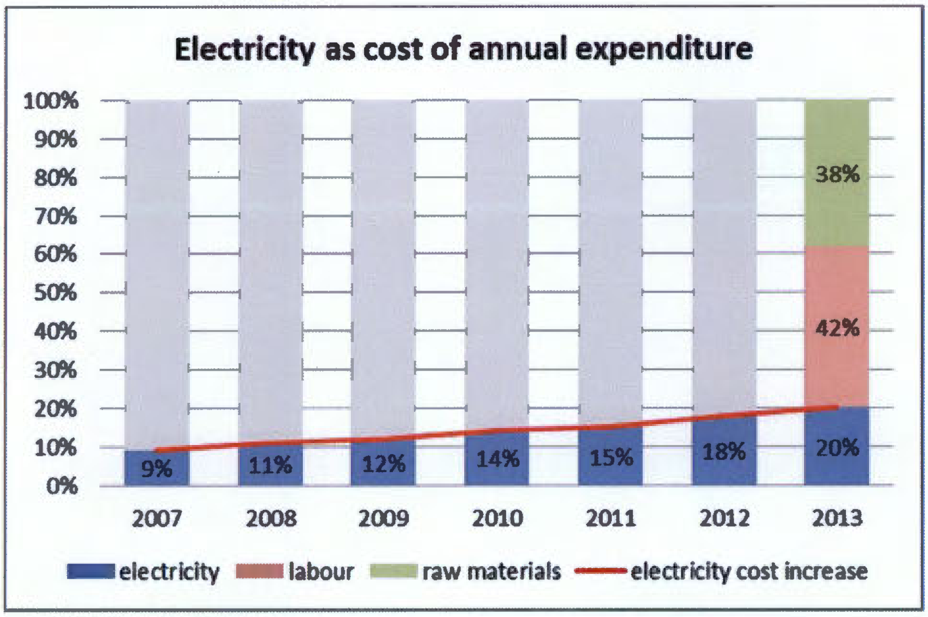

Figure 2: Electricity as cost % of annual expenditure based on (EIUG, 2014)[1]

The energy intensive iron and steel sector in particular, which consumes about 39% of the total electricity consumption of the manufacturing sector, has to overcome the power cuts and the rising electricity prices to remain competitive (Deloitte, 2014). The South African Institute of Foundrymen (SAFI) rates rising electricity prices as the greatest threats to the local foundry industry. Compared to the other BRICS countries the South African foundry industry already uses more electricity per ton produced than their counterparts in other emerging countries (SAFI, 2015). These factors make it imperative for foundries to reduce energy consumption in order to remain competitive and contribute towards the national demand reduction.

This master thesis will examine the current energy situation of one of the largest electricity consumers in the Cape metropolitan area. The foundry under review supplies motor blocks to the

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[1] No data available for labour and raw materials for 2007-2012

automotive sector, an industry which faces challenges due to the present energy crisis in South Africa. The foundry has implemented a number of energy efficiency measures already and will be evaluated for their effectiveness.

1.2. Objective

This thesis' objective is to identify energy efficiency improvements for the South African foundry industry, which are both cost-effective and environmentally friendly. For the accurate identification a number of sub-objectives are set:

- Assimilate relevant background information about the South African foundry industry and energy status quo
- Determine energy usage and energy intensity of foundry under review
- Evaluate already implemented energy efficiency measures
- Define and evaluate possibilities to improve energy usage

1.3. Scope and Limitation

The majority of the literature reviewed explaining the foundry process as well as energy efficiency measures in the foundry industry, is based on international research and case studies. Most of the relevant research has been executed in Sweden and Canada, countries which are historically known for a large foundry industry and pioneers in energy efficiency. A lack of research regarding energy efficiency in South African foundries has been identified.

Therefore, this thesis offers the South African industry an insightful view on energy intensity and energy optimization measures already implemented. However, the analysis of actual energy intensities and evaluation of implemented energy saving methods were only conducted at one single foundry. A critical mass was not reached as a site-specific case study approach was chosen, hence it should be mentioned that the findings have limited global validity.

1.4. Outline of the Thesis

The first chapter, the “Introduction”, gave the background and objective of this thesis. The following chapter is the “Literature Review”, giving a brief presentation of the foundry industry as well as the foundry process. Available literature on the energy consumption and energy efficiency possibilities relevant for this thesis are reviewed and described in more detail. The “Methodology” chapter describes how data was obtained and analysed. In the next chapter, the results from the case study are presented and discussed, while in the last chapter “Conclusions” a short summary is given with concluding remarks.

2. Literature Review

2.1. South Africa's Foundry Industry

The South African metal-casting industry has experienced a period of decline. The number of foundries in South Africa has declined by 36% since 2007, with currently 170 foundries in operation. The total annual production of foundry output is estimated at 375,240 tons, while steel products with about 100,000 tons of steel products and 155,000 tons of grey iron comprising the main outputs (SAFI, 2015).

John Davies, the CEO of the SAIF, reasons that the decline of the industry is due to underinvestment, a widening skills gap and foreign imports. The South African foundry industry predominantly manufactures for the domestic market. Nonetheless, as the South African trade figures suggest, there are still more imported than locally produced castings (Slater, 2015). National infrastructural reconstruction and development plans, as well as the aim to manufacture 1.2-million vehicles by 2020 coupled with high localisation requirements, however, signals a more stable period for foundries (Rodin, 2014), especially given that 30% of all foundries work as supplier for the automotive sector (SAFI, 2015).

However, the steel and iron industry has to overcome the challenge of rising electricity prices and interrupted electricity supply. As previously mentioned, SAFI rates the rising electricity prices as the greatest threat to the industry. To remain competitive, the local foundry industry has to introduce solutions to meet these challenges (Deloitte, 2014; SAFI, 2015).

2.2. Foundry Specific Technologies

2.2.1. Foundry Process

In order to understand the energy consumption and identify possible energy optimisation opportunities, the production process in the foundry must be understood first.

The oldest metal shaping technique is to pour molten metal into a refractory mould cavity and allow the metal to solidify. The solidified object is taken out by breaking the mould apart. This object is called casting and the technique followed is the casting process. This process was already discovered around 3500 BC, mainly for the creation of copper axes and other tools (Simha, 2006). Nowadays casting is an industrial process and often the first manufacturing step of any product. The foundry process involves making the mould, melting and pouring the metal into the mould, and finally removing the mould and finishing the product. A typical foundry operation can be split into distinctive sections as illustrated in Figure 3.

1) mould and core making
2) scrap metal melting
3) casting of the molten metal into the mould, solidification and removing the casting from the mould
4) finishing of the casting

This thesis will focus on iron casting from ferrous melting. Cast iron can be melted in induction, rotary, cupola and electric arc furnaces (Prevention, 2004).

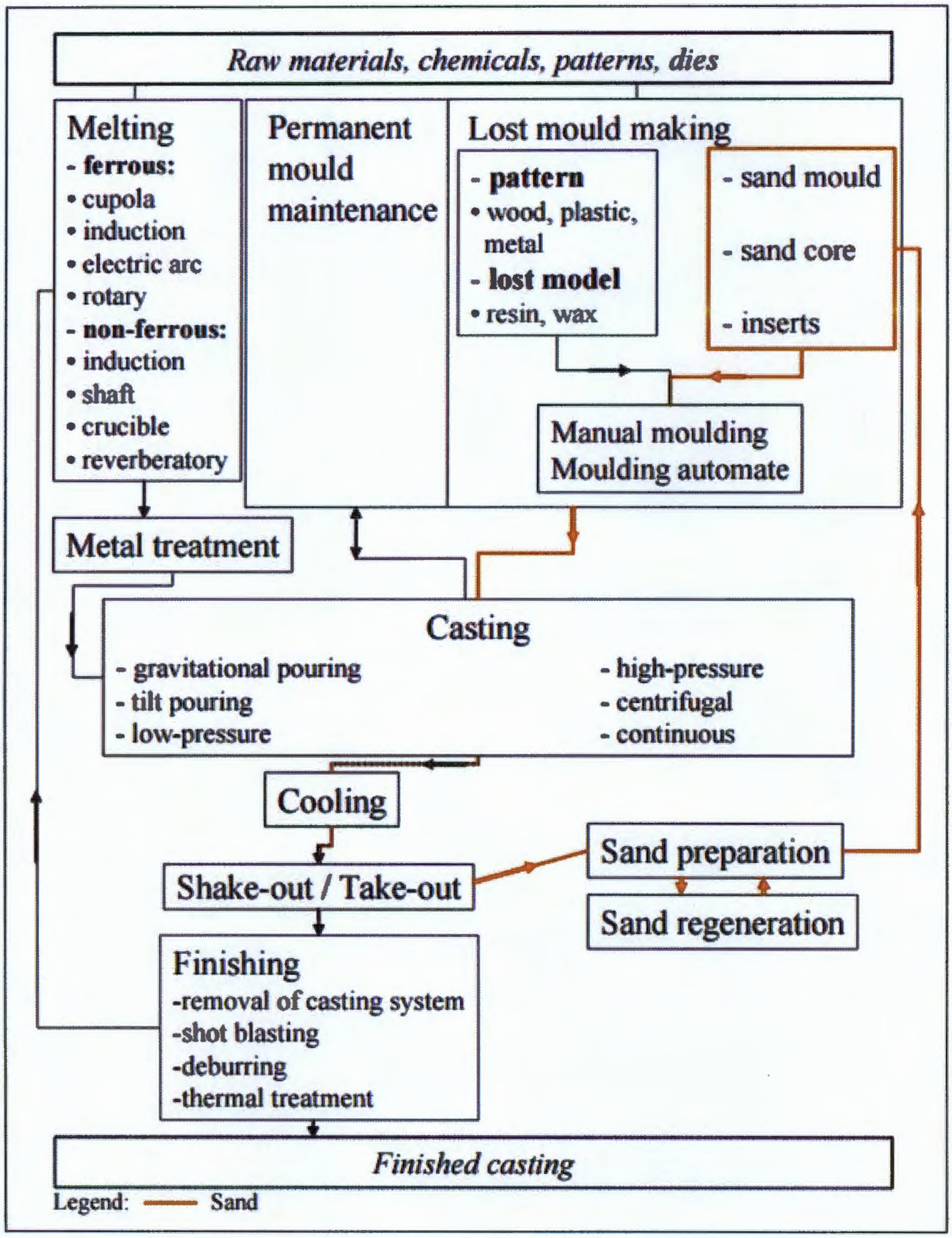

Figure 3: The Foundry Process
(Prevention, 2004)

2.2.1.1. Moulding and Core Making

Moulding and core making is the production of the mould in which the molten metal will be poured. The mould thereby defines the outer shape of the casting, while the core defines the inner one.

Moulds can be classified in two different types, the lost moulds (single use only) and permanent moulds (multiple uses). Mostly lost moulds are used in iron casting, where for each casting a mould is made and destroyed after the pouring. The moulds are made of sand, whereby sand is mixed with clay and water or with chemical binders, and then packed or rammed around the pattern to form the mould (Prevention, 2004).

For the manufacturing of metal castings with internal geometry the use of cores are necessary. A core is a replica, (actually an inverse), of the internal features of the part to be cast. The core is commonly made out of the same material as the mould and stays in the mould while pouring the liquefied metal. Once the metal is solidified the core is broken up and removed together with the mould. Cores are produced by blowing and ramming in heated processes, investing sand into a core box, and usually make use of compressed air to compress the sand into a specific shape (CTI, 2004).

While cores are formed using chemical binding systems, commonly, green sand is used for the moulding. Green sand is also known as tempered or natural sand, which is a prepared mixture of silica sand with 18 to 30 percent clay, having moisture content from 6 to 8%. This sand is an easily available and low cost raw material. It is commonly employed for production of ferrous and non-ferrous castings (Simha, 2006). Green sand uses its moist sand mix with the clay and water mixture act as a binder holding the sand grains together. Nonetheless, the sand has to be dried to the specific moist content as it usually contains metallic elements such as flashes, pouring drops, or even small parts of castings from previous processes. All these parts have to be removed by a magnetic iron or by Eddy current separators. Furthermore the sand has to be cooled to keep the moisture level as constant as possible (Prevention, 2004).

2.2.1.2. Melting Process

The selection of the melting furnaces is an important aspect of the casting process. Each furnace type has its own advantages and disadvantages, depending on charge material and energy requirement.

The melting process involves a number of steps, as in Figure 4, for the induction furnace illustrated. Before the scrap metal is melted it must be prepared accordingly. Therefore dirt and moisture must be removed and sometimes the charge material can also be preheated. To melt the charge material energy from combustion of fuels or direct heating with electricity will raise the temperature above the melting point to a pouring temperature. Furthermore, the molten metal needs to be maintained in a molten state until it is ready for tapping. Tapping is the transfer of the molten metal to the transport ladle, from where it will be moved to the point of final pouring in the mould (Naranjo, Kwon & Majumdar, 2005).

Often the molten metal is held in a separate holding furnace before pouring in the mould. This allows continuous supply of molten metal and an uninterrupted pouring into the moulds. However, as Naranjo (2005) states, the holding process increases energy consumption as a large amount of energy is used to maintain the metal in the molten state. Ideally molten metal is directly transported to the pouring station, which makes the holding furnace dispensable.

The ladle can also be preheated with gas burners before being filled with molten metal, to reduce energy loss due to convection. This method will be discussed later as an energy saving opportunity.

Melting Technologies

This sub-chapter describes different types of melting technologies available in the metal casting industry. Different melting furnaces derive their energy to heat up the metal from different sources. Typically used are solid fuels such as coke and breeze, natural gas or electricity. Conversely, also non-conventional melting technologies are evolving, such as solar furnaces (Naranjo, Kwon & Majumdar, 2005).The focus on this literature review will, however, be on commonly used technologies, such as cupola, electric arc and induction furnace.

Electric Arc Furnace

Electric arc furnaces (EAF) use direct current electricity and allow the direct melting of iron, such as scrap metal. The metal is melted by the heat, which is generated between electrodes and the charge in the holding bath of the EAF. Typical power levels for three-electrode furnaces range from 10 MW up to 80 MW, with electrode currents varying between 10 kA and 60 kA, and electrode voltages ranging from 100 V to 2000 V (Boulet, Vaculik & Wong, 1997).

Cupola Furnace

The main difference between the cupola furnace, the EAF and induction furnace is that combustion takes place and the heat from the combustion causes the charge to melt. Due to its low cost and simplicity, the cupola used to be the primary method for melting iron (Abdelrahman & Moore, 1997).

The cupola is charged at the top with coke, a fuel made through the pyrolysis of coal at high temperatures (~1000 °C) for several days (Leth-Miller et. al, 2003). At the bottom of the cupola, air is injected and this blast air is often heated and mixed with oxygen. As the coke burns at the bottom, the charge drops and melts, producing a continuous flow of molten iron, with up to 100 ton/hour (Moore et. al, 1998).

The thermal efficiency of cupola furnace is the ratio of the heat utilized in melting and the heat evolved in it. That evolved heat is due to burning of coke, due to oxidation of iron and heat supplied by the air blast. Literature suggests that approximately 48-70% of the evolved heat is lost in the process (Simha, 2006).

Induction Furnace

The induction furnace is the most common type of batch melting. The induction furnace uses electricity as a fuel source; other than the electric arc furnace it uses alternating current, however. The alternating current flows through a coil creating an electromagnetic field which directly heats up the charge material. The benefit compared to the cupola furnace is that there are fewer chemical reactions and therefore it is easier to achieve melt composition. The efficiency of induction furnaces lies between 50 and 70% (Naranjo, Kwon & Majumdar, 2005).

The induction furnace will be discussed and analysed in detail in chapter 2.3.

Further, the process scheme with a coreless induction furnace will be outlined. The process generally consists of melting – tapping – metal treatment – pouring (CAEF, 1997).

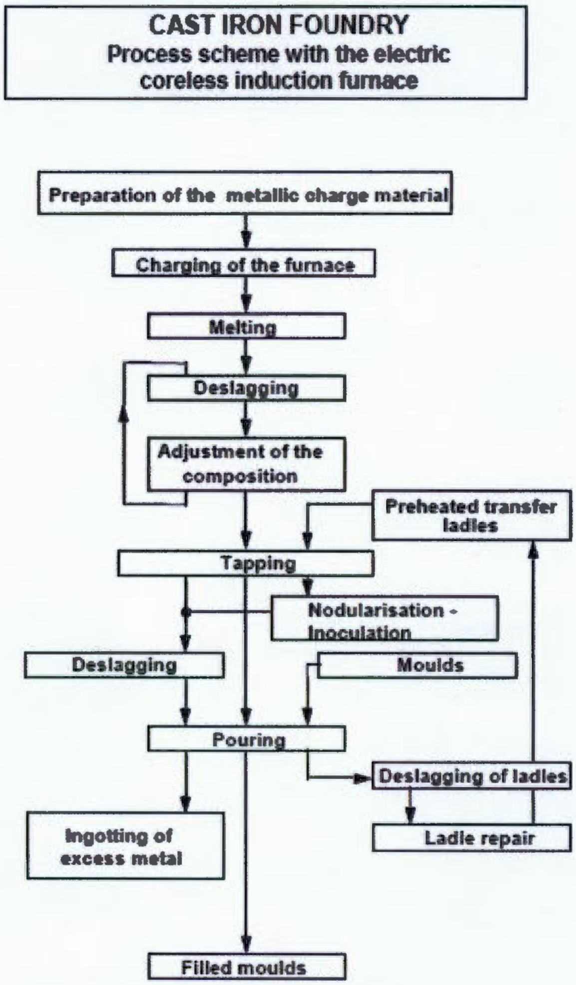

Figure 4: Foundry Process with Coreless Induction Furnace (CAEF, 1997)

2.2.1.3. Casting

Finally the molten metal is poured into the finished mould under the effects of gravitational or centrifugal forces. Molten metal is poured into moulds using various types of ladles, or in high volume production, automated pouring furnaces. Metal is poured into the "runner" (a channel into the mould cavity) until the runner bush is full. The "riser" provides an additional reservoir of feed metal to counteract the shrinkage that occurs as the casting begins to cool. When the metal has cooled sufficiently for the casting to hold its shape, it is separated from the mould by mechanical or manual methods. Where sand moulds are used, the process is often referred to as shakeout or knockout (CTI, 2004).

A pressure pour furnace can be used on an automated casting line. Pressure pour furnaces are used for holding the melted metal at tapping temperature while casting into the moulds. A large enough pressure pour furnace, allowing continuous refilling, can eliminate the earlier mentioned holding furnaces (Gandhewar, Bansod & Borade, 2011).

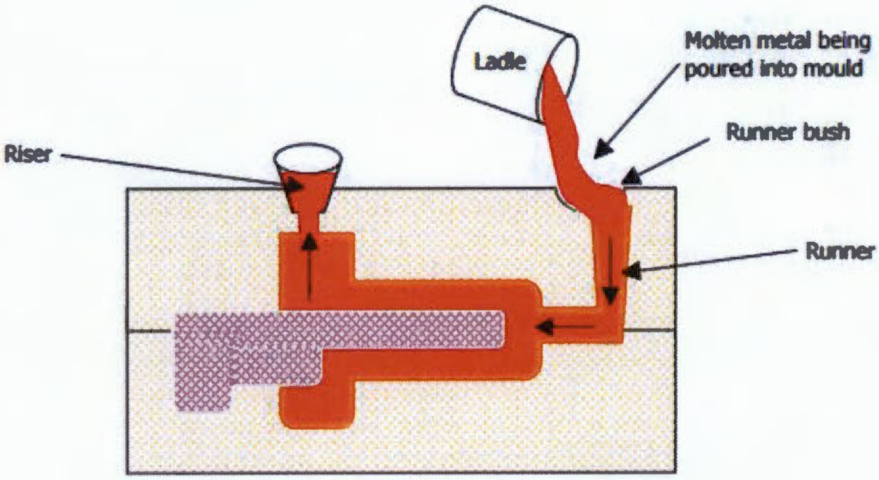

Figure 5: Casting Process
(CTI, 2004)

2.2.2. Characteristics of Induction Furnace

The technology of induction furnaces reaches as far back as the discovery of the electromagnetic induction by Michael Faraday; the first operational induction furnace was, however, only used around 1900 in Sweden (Gandhewar, Bansod & Borade, 2011). Induction furnaces have increased their capacity and can successfully compete with cupola melting. The benefit of the induction furnace is that there are fewer chemical reactions to handle, which helps to achieve the ideal melt composition. As a downside, induction melting is more sensitive to the charge materials, which limits the type of scrap which can be used (Naranjo, Kwon & Majumdar, 2005).

Electric induction furnaces, other than electric arc furnaces, use alternating current (AC), with overall efficiencies in the 50-70% range and heat loss to cooling water accounting for 20-25% of the total input (CIPEC, 2003). The primary advantage of induction melting is that the heat is directly generated within the material itself, giving very fast melting times and high efficiencies (Callebaut, 2014). Due to the development of flexible, constant power-tracking, medium-frequency induction power supplies, the new generation of induction furnaces is used for batch melting processes in modern foundries. The power units incorporate heavy-duty silicon-controlled rectifiers which can generate both the amperage and frequency for batch melting, and can achieve electrical efficiencies of up to 97%. Modern induction furnaces are capable of melting almost 60 tons per hour and small furnaces with high power densities of 700 to 1000kWh/ton can melt a cold charge in 30 to 35 minutes (Naranjo, Kwon & Majumdar, 2005).

Induction furnaces are classified into two basic designs, the core type or channel furnace and the coreless. The channel furnace is mostly used in smaller foundries or/and for larger castings. The coreless furnace is widely used when a quick melt of one alloy is needed, or when it is necessary to vary alloys often (George, 1985). The following figure shows an illustration of a channel furnace.

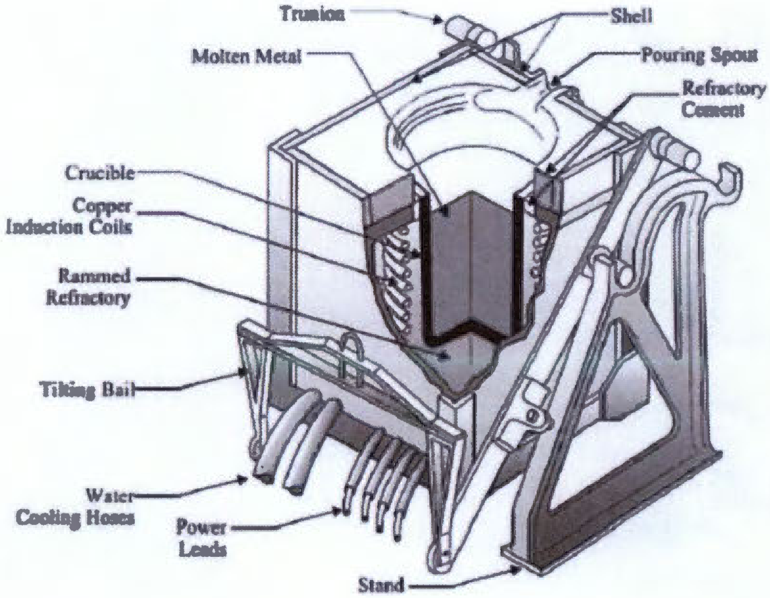

Figure 6: Illustration of Coreless Induction Furnace (Gandhewar, Bansod & Borade, 2011)

2.2.2.1. Principles of Electromagnetic Induction

The principle of induction melting is mainly based on two physical phenomena, the electromagnetic induction and the joule effect. The energy transfer to the metal to be melted within the furnace occurs by electromagnetic induction. An alternating current is induced in a loop of conductive material when this loop is placed in an alternating magnetic field. When this loop is short-circuited, the induced voltage will cause a current to flow, that opposes its cause – the alternating magnetic field. This is also described as the Faraday-Lenz law. If a conductor is placed in the alternating magnetic field instead of a short-circuited loop, eddy current will be induced. The load of an induction furnace is therefore heated as a result of the Joule effect, which can be described as $P = R*I^2$. Due to the uneven distribution of the currents over the charge material this equation cannot be used directly (Callebaut, 2014).

However, knowing that:

$$R = \frac{\pi d * \rho}{A} \qquad \text{Eq. (2.3.1)}$$

$$A = h * \delta = h * \sqrt{\frac{\rho}{\pi * \mu_0 * \mu_r * f}} \qquad \text{Eq. (2.3.2)}$$

$$I = h * H \qquad \text{Eq. (2.3.3)}$$

Simplified the power requirement can be calculated by inserting that into $P=I*R^2$ and adding correction factor F and C

$$P = \frac{\pi d * \rho}{h * \sqrt{\frac{\rho}{\pi * \mu_0 * \mu_r * f}}} h^2 * H^2 * C * F = \quad \pi d * h * H^2 * \sqrt{\pi * \mu_0 * \mu_r * f} * C * F \qquad \text{Eq. (2.3.4)}$$

where

R = resistance [Ω]

I = current [A]

P = power [W]

d = diameter of the cylinder [m]

h = height of the cylinder [m]

H = magnetic field intensity [A/m]

ρ= resistivity [Ωm]

μ_0 = magnetic permeability of vacuum (4π.10-7 H/m)

μ_r = relative permeability

f = frequency [Hz]

C = coupling factor

F = power transmission factor

The two factors C and F correct relative dimensions of the inductor and the load, and respectively the relation between the penetration depth and the external dimensions of the load (Callebaut, 2014).

Form equation (2.3.4) it can be concluded that:

- Power can be increased by an increase of the frequency of the alternating electric current (*f*)
- the magnetic field intensity (*H*) can be increased by the number of ampere-windings,
- Material characteristics (ρ and μ_r) are an important factor (Callebaut, 2014).

2.3. Energy Consumption Pattern of a Foundry operating Induction Furnaces

For the energy-intensive foundry industry in South Africa, rising electricity prices are considered to be the greatest threats to the industry and must be addressed (SAFI, 2015). Industrial companies are affected differently by power cuts and increased energy costs; the impact of the energy costs lies in the relation to the added value. A study of a number of Swedish foundries has shown that foundries are facing electricity cost adding up to 5-15% of overall cost (Thollander et al, 2005). According to a survey commissioned at the end of 2012 by the National Foundry Technology Network and the SAIF South Africa's foundries, energy costs are the highest, accounting to 16% of the overall cost and about 150 USD/ton or 1860 ZAR/ton[2] (Mitchell, 2013). Foundries are therefore dependent to hold their energy consumption and costs as low as possible.

In order to reduce energy consumption it is important to identify where and how energy is being consumed. Fore identified the main energy consumers in the South African foundry industry, shown in Figure 8 (Fore & Mbohwa, 2010). While the furnace itself, heat treatment, core making and heating use the bulk of electricity, lighting, cooling and compressors also cumulatively account for a significant electricity usage. Another study shows that Canadian foundries use 59% of their overall energy for melting, while electric motors consume 12% and compressors 5% (Whiting, 2001). A study on five different foundries in India has shown that on average 77% of their overall electricity consumption is used by melting (Arasu & Rogers, 2009). Even though the different literature reviewed does not clearly state what sizes the furnaces are, what capacity they operate at or what furnaces they operate, all studies agree that the largest consumption is the

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[2] given currency exchange rate 13/07/2015, USD/ZAR 12.41

melting operation, but nonetheless the other energy consumers should not be neglected. The case study of the Indian foundries shows, for example, that compressed air only uses 5% of the overall consumption. However, that still represents a consumption of 21 MWh/month (Arasu & Rogers, 2009).

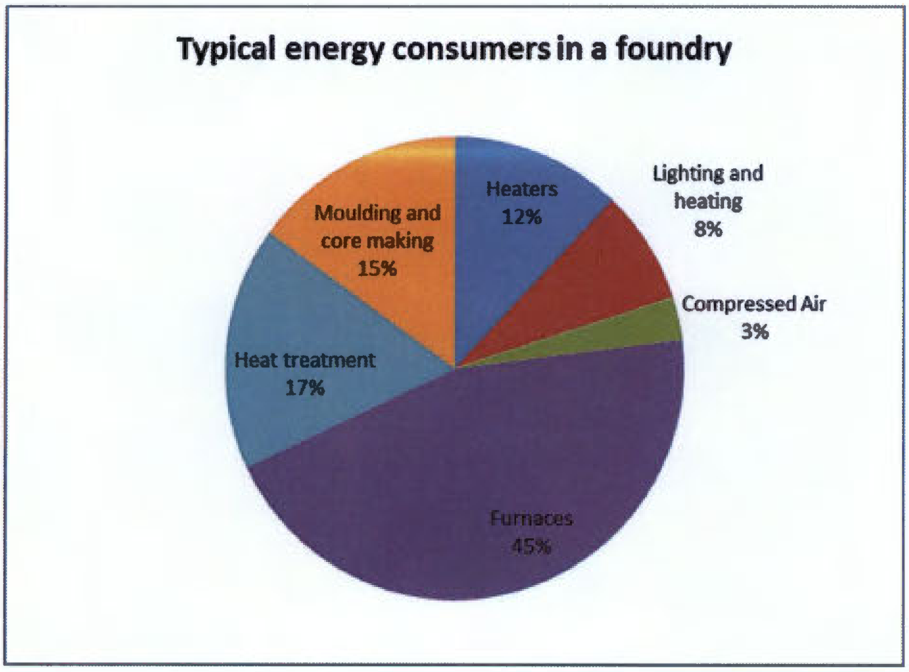

Figure 7: Typical energy consumers in a foundry
(Fore & Mbohwa, 2010)

As melting is the largest energy consumer, the efficiency of the melting operation should be calculated in order to determine if possible energy measures are possible. The energy required to melt one ton of metal in a foundry is significantly higher than the theoretical minimum requirements. The theoretical energy requirements, or also called power consumption rate (kWh/ton), can be calculated for melting and annealing processes. However, the large variety of different processes involved in the casting process makes it difficult to calculate the actual requirement. The theoretical heat energy can be calculated by:

$$Q_{th} = Q_m + Q_{sh} + Q_s + Q_{en} - Q_{ex} \qquad \text{Eq. (2.4.1)}$$

with

Q_m = amount of energy required to melt 1t of charge material [MJ]

Q_{sh} = amount to superheat the melt [MJ]

Q_{en} = energy for endothermic process [MJ]

Q_{ex} = energy for exothermic process [MJ]

and theoretically $Q_{en} = Q_{ex}$

where

$$Q_{th} = Q_m + Q_{sh} + Q_s \qquad \text{Eq. (2.4.2)}$$

And

$$Q_m = Mc(\theta_1 - \theta_0) + ML \qquad \text{Eq. (2.4.3)}$$

$$Q_{sh} = Mc_m\theta_{sh} \qquad \text{Eq. (2.4.4)}$$

$$Q_s = K_sG_s \qquad \text{Eq. (2.5.5)}$$

With

M = mass of charge [kg]

c = specific heat capacity of charge [J/kg K]

c_m = average heat capacity of molten steel [J/kg K]

L = latent heat of fusion of steel [J/kg K]

θ_1 = melting temperature of charge [°C]

θ_0 = initial charge temperature [°C]

θ_{sh}=amount of superheat temperature, taken as 50°C

K_s = quantity of slag formed, average 8% of furnace capacity [kg]

G_s = heat energy of slag [J/kg K]

(Mansoor & Shahid, 2014)

Therefore the theoretical energy requirement can be calculated by determining the total energy content (enthalpy) of the metal at tapping temperature and subtracting that from the total energy at ambient temperature. The theoretical energy requirement for grey cast iron, with melting point at around 1500 degree Celsius is thus 351.5 kWh/ton (Schifo & Radia, 2004).

The actual power consumption rate is also dependent on the furnace capacity. A study by UNIDO (1998) has found that the energy requirement is lowered as the furnace capacity increases until about 12 to 15tons, thereafter the energy requirement remains unchanged, as shown in Figure 9. A research of four induction furnaces in India has shown an average of 620kWh/ton (Arasu & Rogers, 2009), while a study by the US Department of Energy has shown an industry average in the U.S. of 796kWh/ton (Schifo & Radia, 2004). A best practice minimum in the U.S. study was found to be 538kWh/ton (Schifo & Radia, 2004), while South Africa shows the highest average with 859kWh/ton according to SAFI's survey (Mitchell, 2013).

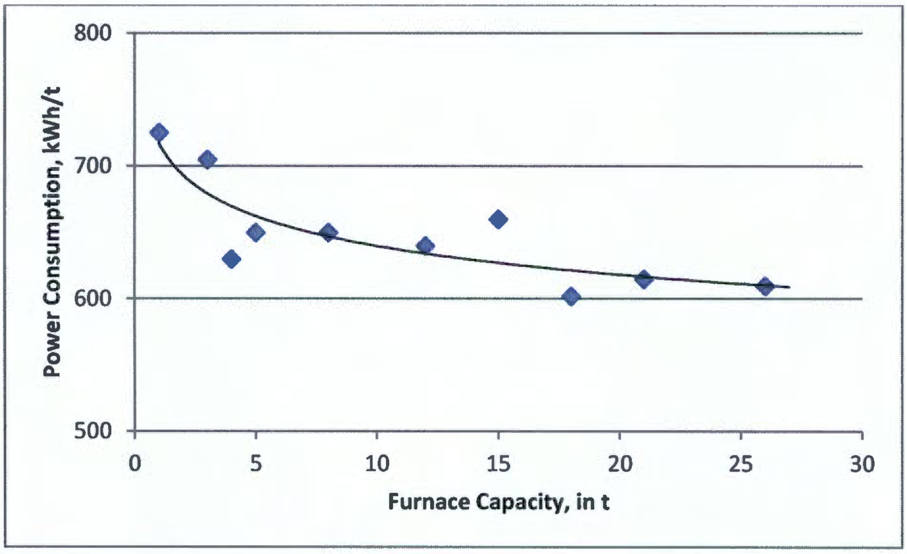

Figure 8: Relation of Furnace Capacity and Energy Requirement based on (UNIDO, 1998)

From given data it can be concluded that melting metal is somewhat inefficient and literature suggests that induction furnaces have a thermal efficiency of 50-70% (Schwam D, Wallace J.F

& Wannasin J., 2005), electrical efficiency can be as high as 97% however (Gandhewar, Bansod & Borade, 2011).

The energy efficiency of the melting process is calculated by the theoretical energy minimum and by the actual amount of energy consumed in melting process (Naranjo, Kwon & Majumdar, 2005).

$$\eta = \frac{Q_{th}}{Q_a} * 100 \qquad \text{(Eq. 2.5.6)}$$

With

η = energy efficiency [%]

Q_{th} = theoretical energy minimum [kWh/t]

Q_a = actual required energy [kWh/t]

Several factors affect the energy efficiency of furnaces. Heat losses consist of conduction loss of heat escaping the furnace wall, radiation loss from the melt surface, absorption loss, slag melting loss and others. Electrical losses are mainly in transformers, frequency converters, condenser, wiring, cabling and coil. The overall efficiency of an induction furnace is therefore the total energy input deducted the electrical and thermal losses (UNIDO, 1998).

2.4. Energy Efficiency Opportunities in Foundries

Literature (Thollander et. al, 2005; Naranjo, Kwon & Majumdar, 2005; Prashanth et. al, 2014; CIPEC, 2003) suggests a number of potential energy efficiency measures which can substantially reduce energy costs in foundries. Most analyses have commonly identified the largest possible energy savings in the melting and holding processes. Proposed measures include focusing on new induction furnaces, waste heat recovery and pre-heating facilitation (Thollander et. al, 2005; Naranjo, Kwon & Majumdar, 2005; Prashanth et. al, 2014; CIPEC, 2003).

Apart from the energy usage for the casting process also supporting processes, like ventilation, pumps and fans, compressed air and lighting are often identified having energy saving potential.

At times these areas are neglected due to historical low energy prices and compared to the furnace itself, having a small consumption (Thollander et. al, 2005). A study on Canadian foundries has shown, as illustrated in Figure 10, that the highest energy saving potential actually lies in fan and pump optimization as well as lighting, while the melting still represents the highest overall saving potential (Whiting, 2001).

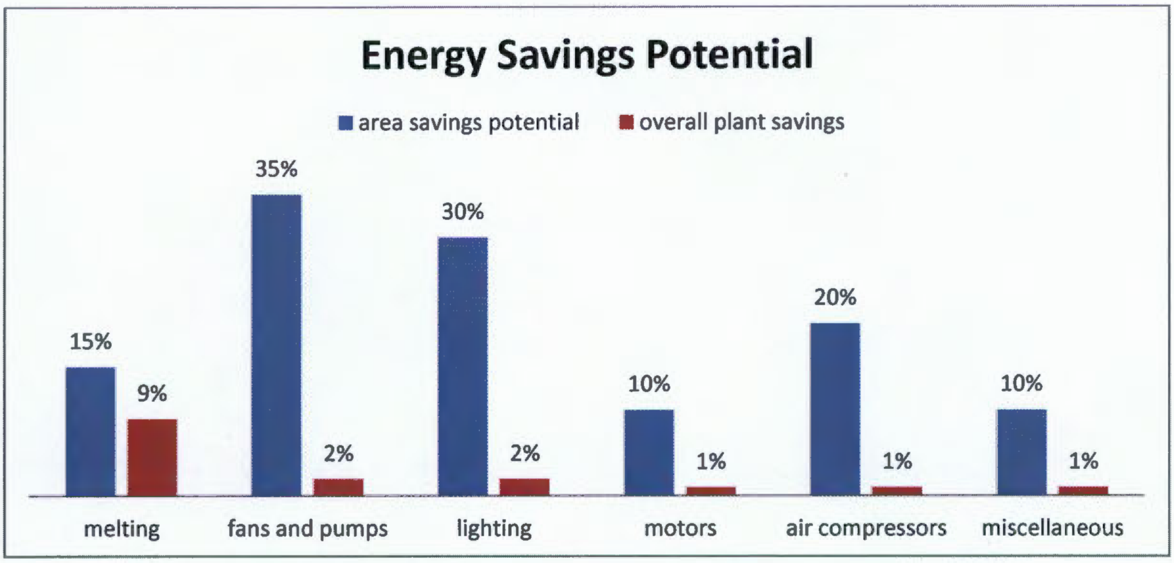

Figure 9: Energy Saving Potential in Canadian Foundries (Whiting, 2001)

The following chapters will discuss energy efficiency opportunities in detail with focus on thermal efficiency possibilities, power factor correction, load management, compressed air and lighting.

2.4.1. Lighting

Often lighting is neglected in energy saving considerations in energy intensive industries, as the common sense focuses on larger single energy users. However, as shown in Figure 10, it offers a great saving potential and is mostly a so called "low-hanging fruit", an energy efficiency project which is easily implemented and can save a vast amount of money. Many energy audits show that much light is wasted and that much energy can be saved by simple behavioural changes (switching off when not needed) and new technologies (CIPEC, 2003).

For energy conservation of lighting, a number of measures can be applied. As mentioned previously, simple reducing of lighting time, by switching off lights when unnecessary can already achieve high savings. Manual switching off requires a behavioural change and involvement of staff, hence another method would be to install automated switches or timers. Furthermore old bulbs can be replaced by high efficiency lighting, such as LED or fluorescent lamps (ERC).
Most industries use lighting replacement of one of their first energy efficiency methods, replacing incandescent lights with fluorescent lights and replacing metal vapour tubes with metal halides, which show very high savings (Debbarma, SR, Kundu & Vineet, 2013).

Responding to the energy shortage in South Africa coupled with the National Energy Efficiency Strategy, Eskom launched a rebate programme to promote the implementation of energy efficient technologies in late 2004. From 2013 a number of different programmes were released, which will be described briefly:

- Standard Product Programme offers rebates for energy savings achieved through specific technologies. The focus of this programme is on small to medium projects which save less than 250kW,
- Standard Offer Programme offers payments at a fixed rate for a fixed period, if a savings from 50kW to 5MW can be verifiable delivered. Depending on the technology used Eskom incentives the saved kWh from 0.42 – 1.2 ZAR,
- Performance contracting is aimed at Energy Service Companies (ESCos) and is bulk buying of energy savings from a single project developer for multiple projects. The minimum project size must be 30GWh saving over a three year period. The benefit for the company where the lighting project is implemented is that no costs occur, as the project developer will pay for the equipment (Ndlovu, 2012).

The programmes mentioned are currently on halt as Eskom had discontinued the funding owing to cash-flow uncertainties. Yet, Eskom has decided to restart the programmes this year again with the target of saving 975 MW (Creamer, 2015c).

Simply changing the light bulbs, however, has to be taken with care. Adequate lighting levels in specific areas of operation have to be considered when choosing a replacement. A research in Canadian Foundries has shown that replacing lighting can result in a non-desirable reduction of lumen/m², hence illumination standards for foundries in Canada haven been developed, as shown in Table 1 (Whiting, 2001). As there were no standards found for South African foundries these values may also be applied to a South African context.

Required lighting level[3]	
Area	lumen/m²
Moulding	1100
Pouring	500
Core Making	800
Grinding	1100
Inspection	1100

Table 1: Required Lighting Level (Whiting, 2001)

2.4.2. Thermal Efficiency Possibilities

When introducing an induction furnace it is important to fully understand the specific features and requirements that are needed. With the right understanding a correct decision can be made on the size and shape of charge material, size of furnace and the connection with pouring line and layout of the melting shop (UNIDO, 1998).

Once an induction furnace is installed, there are different retrofitting technologies to improve energy efficiency. Options to improve energy efficiency in the melting process are preheating of the charge materials, heat recovery systems and operational adjustments such as insulation of the furnace or management of lid-off periods (Prashanth et al, 2014). Table 2 below shows estimated efficiency savings for different retrofit possibilities. This chapter will discuss charge preheating, waste heat recovery and ladle heating.

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[3] optimal lighting level for workers aged 40 years and younger

Retrofitting Efficiency Technology	Estimated Savings
Charge Preheating	5 – 10%
Operational Adjustments	0 – 30%
Waste Heat Recovery	10 – 30%

Table 2: Estimated Efficiency Improvement from Retrofitting Technologies (Albany Research Center, 2005)

2.4.2.1. Waste Heat Recovery

A significant part of the electrical energy required by an induction furnace is converted into waste heat. The cooling system alone wastes about 20 – 30% of the total energy input and in an un-pressurised system the cooling water temperature is usually between 60 – 70°C. To use that heat efficiently, radiators would need to have extra-large surfaces; furthermore the returned water cannot be less than 30°C as this could cause condensation problems. Therefore heated cooling water could only be used for space heating or water heating. A worthwhile application must be reasonably close by and require heat when it can be utilised from the furnace (Prevention, 2004). In South Africa, however, there is only limited use for space heating; only water heating for showers might be usable.

Others actually argue that instead of utilising the waste heat, it is recommended that waste heat production is reduced (Prevention, 2004). A simple change would possibly be to install an automatic lid for the furnace. Operational experience in a German cast iron foundry showed that the furnace lid is open on average for 25 % of the working time of the furnace (Prevention, 2004).

2.4.2.2. Charge Preheating

The quantity of heat required is that required to reach about 1400°C, the melting point of the scrap metal. And further about 65% of the total heat consumed for heating up the cold charge material to tapping temperature (1450-1500°C). Remarkable savings can be achieved by preheating the charge material to about 400-500°C by any technology more effective than induction heating. Preheating could also be done with heat recovered from a previous process (UNIDO, 1998). Other advantages of charge preheating, besides the reduced heating requirement, are the removal of moisture out of the charge material and the reduction of melting time (Naranjo, Kwon

& Majumdar, 2005). This also confirms the conclusion of Eq. (2.3.4) that material characteristics are an important factor of the power consumption.
There are many different methods to preheat the charge; the most common ones using waste heat, are the ones using exhaust gas of the furnace. The hot gases released after the complete melting of the charge material can be reused to preheat the new load of charge material in the range of 450°C and 600°C, ultimately preheating to an average of about 500°C which will reduce the electrical requirements by 30 to 60 kWh/t and time throughput by 5 to 15% (Gandhewar, Bansod & Borade, 2011; Naranjo, Kwon & Majumdar, 2005).

Preheating of scrap charge material is a regular practice with electric arc furnaces. Mostly it is performed in the charging baskets, shaft furnaces or while on scrap conveyors using the waste heat of the furnace. Preheating for induction furnaces is not an adopted practice yet, as most induction furnaces are open-topped and is difficult to capture the waste heat. According to Gandhewar (2011) more efforts in research to develop a comprehensive energy transfer model to link the furnace with the gas generation and scrap preheating is needed.
Nonetheless, preheating can result in a considerable energy saving also with induction furnaces, but the process requires an external heating source. A small rotary or a vertical kiln could be used to preheat scrap with gas (Grzella et. al, 2005). Experimental research from UNIDO has shown savings of 25.4% if preheating the charge material to 450 – 500°C and subsequent melting with a high frequency induction furnace to a tapping temperature of 1500°C (UNIDO, 1998).

2.4.2.3. Improvement of Heat Efficiency

There are a number of simple interventions to improve the heat efficiency of the melting process. Firstly, the tapping temperature should be as low as possible. The heat capacity of the molten metal increases with increasing the tapping temperature and furthermore the heat loss of the furnace is proportional to the melting temperature. The heat capacity of gray iron increases by 20kWh/t when its temperature rises 100°C. The heat conduction loss Q_c and radiation loss Q_R are calculated as followed (UNIDO, 1998:57–58):

$$Q_C = \frac{T-t}{R} * 10^{-3}$$ Eq. (2.5.1.1)

$$Q_R = 5.67 * 10^{-3} * A * \varepsilon * (\frac{T}{100})^4$$ Eq. (2.5.1.2)

With

t = cooling water temperature [°K]

T = molten metal temperature [°K]

R = heat resitance of furnace wall [kW/°K]

A = surface are of molten metal [m^2]

ε = emissivity

From these equations it can be concluded that a lower tapping temperature, or in that case the molten metal temperature T, results in a lower heat conduction and lower radiation loss. Furthermore from equation Eq. (2.3.5), the theoretical minimum requirement, it can be concluded as lower the tapping temperature as lower the specific power consumption requirement. In order to keep the tapping temperature as low as possible some simple measures can be turned into practice. For instance for a medium sized induction furnace the average radiation loss for every minute the cover is left open will result in a loss of 10 – 15kWh (CIPEC, 2003:56). This can be explained with Eq. 2.5.1.2, as heat radiation loss is proportional to the molten metal surface and tapping temperature to the power of four. At a tapping temperature of about 1500°C the loss will equal to 60-70kWh/m^2 with open lid. It is therefore highly important to keep the lid of the induction furnace closed at all possible times (UNIDO, 1998:59).

2.4.2.4. Ladle Heating

Ladles are used to transfer the molten metal from the furnace to the pouring station. Pouring the molten metal into a cold ladle is unwanted, as it will drop the temperature of the liquid steel significantly and influences the steel quality negatively (Gupta & Chandra, 2004:1520). In principal the heat loss in the metal **is** due to conduction into the ladle walls and radiation from the exposed metal to the surface on top (Urquhart, Guthrie & Howat, 1973). Effective insulation of the ladle would reduce conduction, while preheating would further allow a more efficient way of transporting the molten metal (Naranjo, Kwon & Majumdar, 2005). Urquhart et al (1973) have calculated the temperature drop of liquid steel and heat flows during transportation in a ladle. Their theoretical results showed that about 50% of heat loss is into the cold ladle wall, while a preheated wall would minimize that heat loss. The theoretical results show that with an 1100°C heated ladle, the heat loss of the molten metal in 40mins is about 30°C while heating the ladle to 100°C results in a heat loss of 70°C in the same time (Urquhart, Guthrie & Howat, 1973).

Peaslee et al conducted a study on 19 foundries in the United States and several experiments with ladles examining the thermal losses during liquid steel transfer. The focus of the study was to observe the thermal loss depending on different ladle design, refractory material and preheating temperatures. The results of the different ladle heating temperatures can be seen in Figure 11 below (Peaslee et. al 2005).

The preheated ladles show the least heat loss while non-heated ladle shows the largest heat loss. The figures of the values of (Peaslee et. al 2005) confirm the theoretical results (Urquhart et al, 1973).

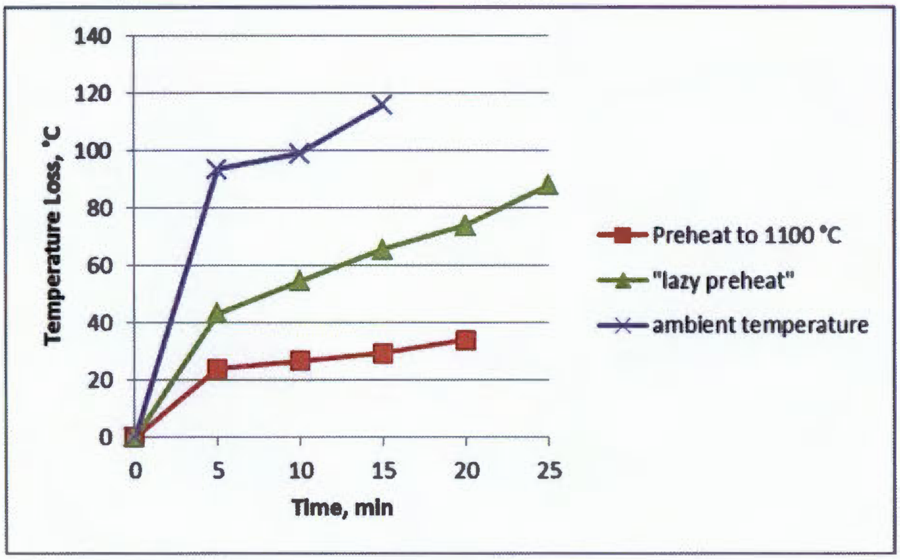

Figure 10: Heat Loss in Ladle
(Peaslee et. al 2005)

Usually a ladle is heated up with open gas flame burners, (Meffert, 1999) and (Urquhart et al, 1973) argue that the flame should reach the bottom of the ladle to achieve best heating results. Other than reducing the cooling down of poured metal and reducing convection loss, heating the ladle will also allow lower tapping temperatures. This would save energy in the melting process from the induction furnaces, as by Eq. (2.4.4).

2.4.3. Power Factor Correction

2.4.3.1. Definition of power factor

Electrical devices in industrial processes, such as induction motors or induction furnaces, require active (P) and reactive (Q) power. The reactive power is required to maintain a magnetic field while the active power is converted into mechanical power (Hänßler & Knoll, 2008). The vector sum of the active and reactive power results in the apparent power or total power (S). The ratio of active or usable power in kilowatts (kW) to the apparent or total power (sum of active and reactive) in kilovolt-amperes (kVA) is the actual power factor (no unit). The power factor, therefore, is the cosine of the angle between those two quantities as represented in Figure 12 (Shwedhi & Sultan).

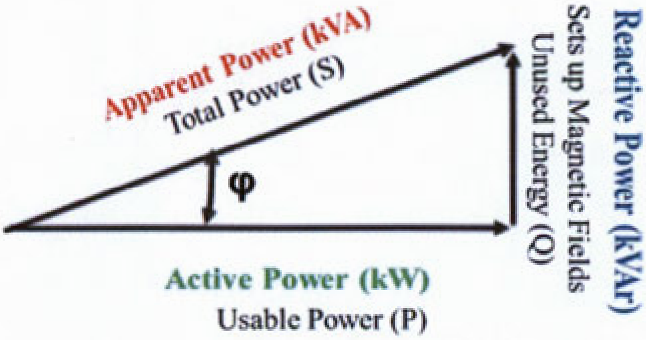

Figure 11: Power Factor Illustration

Theoretically a power factor can vary between 0 and 1, where the value 1 would deliver all of the power as active power and is called unity power. Devices which use inductive coils or capacitors, use a significant amount of energy to create an electro-magnetic field. This power is referred to as reactive power and is measured in kilovolt-amperes-reactive (kVAr). Consequently the power factor can be used as an efficiency measure, representing how efficiently a facility uses electricity as it compares the useful work that is extracted from the total amount of electricity supplied (Shwedhi & Sultan).

Power factor calculation:

$$\mathrm{PF} = cos\varphi = \frac{P}{S} \qquad \text{Eq. (2.5.3.1)}$$

$$PF = \frac{P}{E*I} \qquad \text{Eq. (2.5.3.2)}$$

Equation for apparent power using Pythagoras:

$$\mathrm{S}^2 = \mathrm{P}^2 + \mathrm{Q}^2 \qquad \text{Eq. (2.5.3.3)}$$

$$S = \sqrt{\mathrm{P}^2 + \mathrm{Q}^2} \qquad \text{Eq. (2.5.3.4)}$$

Or

$$\mathrm{S} = \frac{P}{cos\varphi} = \frac{P}{PF} \qquad \text{Eq. (2.5.3.5)}$$

Equation for active and reactive power:

$$\mathrm{P}^2 = \mathrm{S}^2 - Q^2 \quad with \quad P = \sqrt{\mathrm{S}^2 - \mathrm{Q}^2} \qquad \text{Eq. (2.5.3.6)}$$

$$\mathrm{Q}^2 = \mathrm{S}^2 - P^2 \quad with \quad Q = \sqrt{\mathrm{S}^2 - \mathrm{P}^2} \qquad \text{Eq. (2.5.3.7)}$$

2.4.3.2. Power Factor Correction/Improvement

When observing Eq. (2.5.3.2) and Eq. (2.5.3.6) it becomes clear that a smaller reactive power means a better power factor. Figure 13 shows a current diagram of a very lightly loaded motor which has a PF of less than 0.3, represented is a low load current compared to the magnetizing current. Eliminating the magnetizing current would result in reduced reactive power.

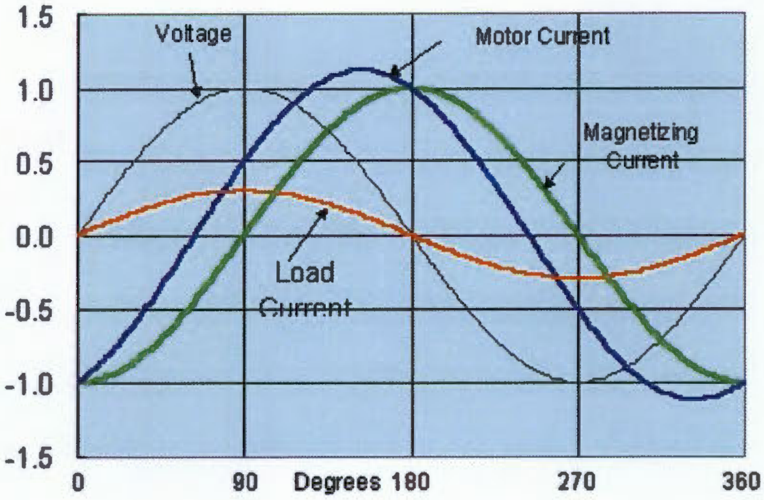

Figure 12: Current diagram of light loaded motor

To eliminate or reduce the reactive power one must understand the process of energy storage in inductive devices and capacitors. The voltage in AC circuits varies sinusoidally, while the voltage passes through the zero point and goes toward the maximum point an inductive device gives up energy from its electromagnetic field. When the voltage starts dropping from the maximum point to zero the capacitor gives up energy and the inductive device stores it as shown in Figure 15. Therefore, when installing an inductive device and a capacitor put parallel on the same circuit, an exchange of magnetizing current to the inductive device will happen and can therefore be seen as an kVAr-generator (Shwedhi & Sultan).

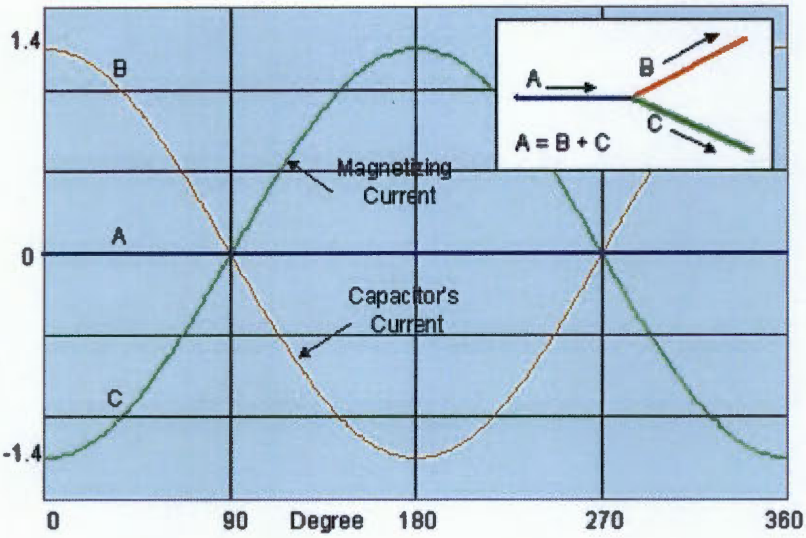

Figure 13: Capacitor current diagram

Literature observes that in most cases the exact figures for the power factor and reactive power are not available. Mostly there will only be access to a wattmeter and ammeter to measure active power, which can be compared against the apparent power which is calculated by the product of total voltage and current (S = I*E). To calculate the reactive power one can use equation Eq. 3.5.7, and with the reactive power the needed size of the capacitor can be calculated (Kuphaldt, 2007).

$$Q = \frac{E^2}{X} \qquad \text{Eq. (2.5.3.8)}$$

$$X_C = \frac{1}{2\pi f C} \qquad \text{Eq. (2.5.3.9)}$$

solving for X

$$X = \frac{E^2}{Q} \qquad \text{Eq. (2.5.3.10)}$$

solving for C

$$C = \frac{1}{2\pi f X_C} \qquad \text{Eq. (2.5.3.11)}$$

Results in required capacitor size

$$C = \frac{1}{2\pi f X} \qquad \text{Eq. (2.5.3.12)}$$

Most devices, however, operate at varying loads and a correct calculation of the required capacitor size is difficult. Compromises have to be made to avoid oversizing and therefore the power factor results tend to be low except of in full load operation (ERC).

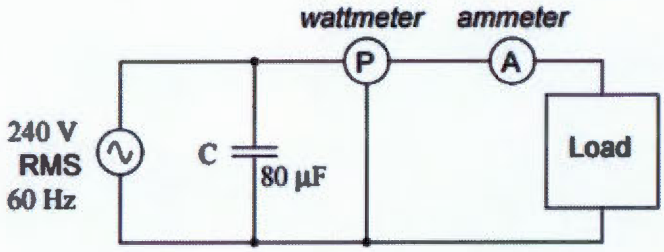

Figure 14: Parallel capacitor correcting reactive power

Facilities with fewer inductive devices can install separate capacitors on each device, as shown in Figure 15, as a low cost option. Larger facilities with a number of devices, however, can use automated power factor correction tools. These tools detect the reactive power demand and switch in banks of capacitors to balance the inductive load (ERC).

2.4.3.3. Benefits of Power Factor Correction

In South Africa industrial and some commercial facilities pay a demand charge in addition to a consumption charge. The demand charge is based on the apparent power (R/kVA), hence a low power factor reflects in a higher electricity bill (DoE, 2008). Investing to improve the power factor therefore has a direct financial benefit, often with a payback of less than one year (ERC).

Load Type	Approximate power factor (half load ... full load)
Induction Motor	<100 kW 0.6 ... 0.8 250 kW 0.8 ... 0.9
Incandescent lamp	1.0
Fluorescent lamp	0.5 ... 0.6
Neon tube lamp	0.4 ... 0.5
Induction furnace	0.2 ... 0.6

Table 3: Example of Power Factors
(Nokian Capacitors, 2002)

Furthermore reducing the inductive loads reduces the current. The reduction of that current may allow the circuit to carry new loads, which could save cost to upgrade the connection to the distribution network when extra capacity is required (Shwedhi & Sultan). This could possibly be the case if an additional furnace should be installed.

Considering that induction furnaces, which are mainly used in South Africa, produce their heat by alternating current from an induction power until flowing through a coil creating an electromagnetic field in order to make electric current flow through the metallic charge and heat it up, one can imagine a possible power factor correction opportunity (Gandhewar, Bansod & Borade, 2011). Especially given that most furnaces currently used in South Africa are about 30 years old and operating at about 70% to 75% utilisation, and even lower in some cases, a power factor correction could be beneficial (Mavuso, 2012).

2.4.4. Load Shifting

The cost of supplying energy for a utility varies according to time of use and seasonal patterns. Eskom always attempts to maintain sufficient capacity to generate electricity to meet the maximum demand, in peak hours the cost of supplying electricity is higher. Summer and winter as well as the time of day have different load profiles as depicted below in Figure 16. The demand in South Africa shows two peaks, one in the morning (07h00 to 10h00) and an evening peak (16h00 to 20h00). High peak demands require Eskom to operate their diesel turbines, which are expensive. Unlike winter, where the demand increases during the evening peak, the demand profile during summer is much flatter (Eskom, 2014). Eskom identified load shifting as a solution to that national problem and therefore Eskom introduced the time-of-use tariff. It sells electricity at rates that reflect these daily and seasonal differences in supply cost. Comparing the national power demand of 2007 and 2014 it is visible that the power demand decreased, which indicates a successful demand side management already. The time-of-use tariff has a large price difference between peak and off-peak periods, ranging from the highest about R3/kWh and the lowest

R0.4/kWh (Eskom, 2015). This large difference in electricity tariffs makes it imperative that foundries should manage their loads and can save a large amount of money by melting in off-peak times.

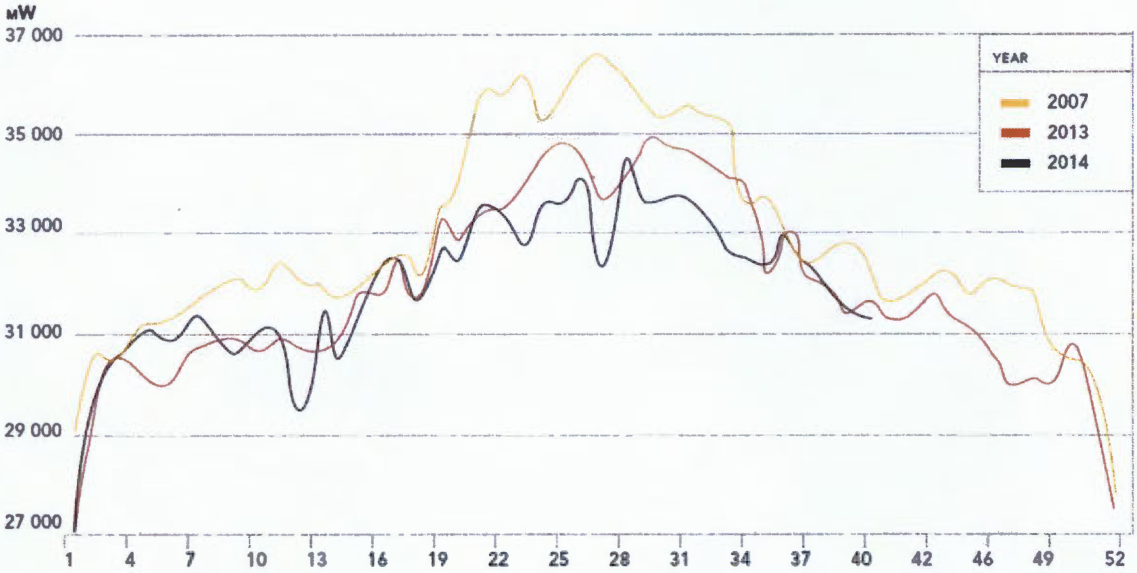

Figure 15: National Power Demand Trends 2007 – 2014 (GreenCape, 2015)

A number of international case studies on load shifting on foundries as well as case studies of South African industry plants exist. However, based on reviewed literature no studies or research have been found on load shifting in a South African foundry. A case study of a successful implemented load shifting project for energy intensive mills at a South African cement plant, however, has showed that the implementation of load shifting in South Africa is viable and that it can show considerable financial savings (Groenewald, Vosloo & Mathews, 2012). While Middelberg et al. (2009) identified significant savings on a South African colliery's conveyor belt optimization and obtained results of shifting 73% from peak periods to standard periods which resulted in a 49% cost reduction. Furthermore Ashok and Banerjee (2000) proved a large potential of load shifting potentials through a case study for arc furnaces in India using time of use tariffs (TOU).

2.4.5. Maximum Demand Management

In addition to the time-of-use tariff, Eskom charges a demand charge (R/kVA). When two or more furnaces operate in a foundry and consume energy in random manner, the furnaces and sub-processes can often overlap resulting in a high energy demand, as case A in Figure17 illustrates. As the energy demand charge is determined by the monthly maximum demand, the latter has a direct influence on the energy bill. Thollander (2005) claims that, the most economically advantageous energy-efficiency measure at the foundry, is to aggregate load-management practices with the foundry's strategic production planning.

Maximum demand management is the process of scheduling the loads to reduce maximum demand. It involves the optimizing of consumption patterns and controlling the equipment accordingly (Ashok & Banerjee, 2000).

In order to regulate the maximum demand the foundry can install a power control system which is aware of the foundry's production schedule. Conventional power control systems work according to a given maximum limit of demand. When the maximum is reached, the furnace will be shut down to a technical minimum. This shut-down of the furnaces can result in a considerable loss of melting time. Modern load management systems use parallel-difference-power control, which controls the furnaces in a parallel and smooth way. The demand is reduced simultaneously for a brief time using an intelligent process control system. To reduce the power consumption in the short term, the demand curves are synchronised as illustrated in case C below (Bosse). The forerunner of modern energy management systems for foundries is a product called Padicon® from Dr.Tannenberger GmbH, a German based company. Padicon® runs the furnaces in parallel and merely reduces their demand simultaneously, using an intelligent process control system based on historic production and consumption data. As longer as the system runs, it harmonises itself (Verma, 2015).

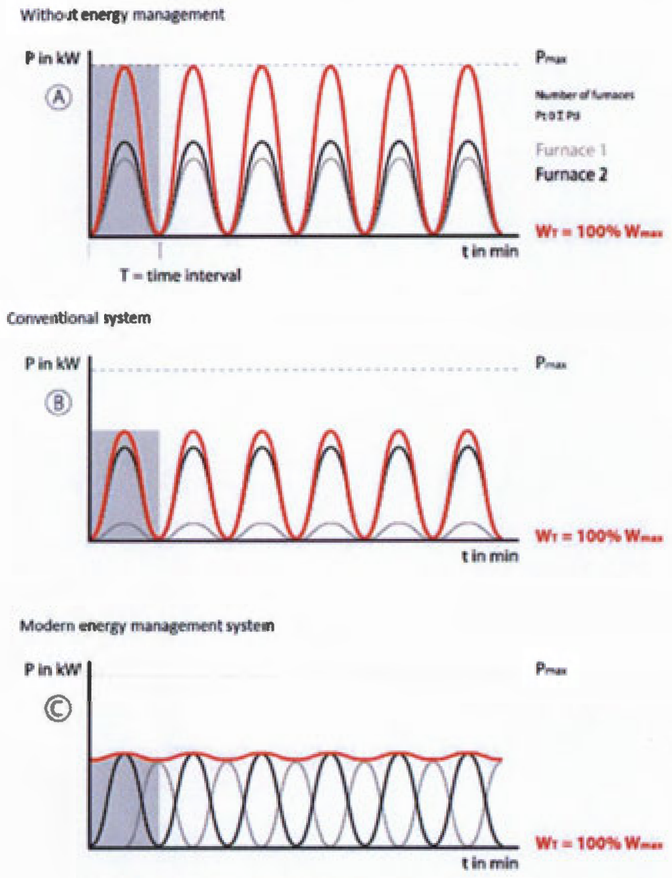

Figure 16: Energy Management System
(Bosse)

In the Netherlands, a foundry with six induction furnaces installed the Padicon® system and reduced their peak load by 39% from 5773kW to 3500kW without sacrificing their production output (Tanneberger, 2010). The literature review has not found studies or research of any installed demand management systems in a South African foundry yet.

2.4.6. Compressed Air Systems

Even though Whiting (2001) suggests that compressed air is only a minor consumer, it is still the most expensive utility in a foundry and offers high potential for saving as Figure 9 shows. Compressed air is probably the most expensive form of power as only 19% of its power is actually usable (Prashanth et al, 2014; Kaya et al, 2002). Yuan et al (2006) analysed the cost of energy delivery modes in the automotive sector and found that compressed air, compared to natural gas, steam and electricity, is as much as doubly expensive (Yuan et. al, 2006). The foundry industry uses a great deal of compressed air for production purposes, especially in the mould and core making process. According to the total life cycle cost of a compressed air system the operating cost accounts for about 75% while investment and maintenance are minor costs in comparison (Koski, 2002).

However, already small modifications can achieve large savings and short payback periods, identifying and fixing leakages, accurate supply and demand match. Matching compressor size to load, reducing the air inlet temperature, usage of a high efficiency motor, and simple behavioural changes can save large amounts of energy (Price & Ross, 1989; Kaya et al, 2002; Neale, Walmsley & Kamp, 2006).

The annual energy usage (AEU) by a compressed air system can be estimated with following Eq. (2.5.5.1) (Saidur et al, 2009).

$$AEU = P * L * hr \qquad \text{Eq. (2.5.6.1)}$$

With

P = full load power of compressor system [kW]

L = load factor [%]

hr = annual operating hours [h]

The next subchapters will discuss possible energy efficiency interventions.

2.4.6.1. Monitoring

From the literature studied, it was found that compressed air is the most expensive form of energy in industrial processes. Yet, Marshall (2014) argues that most compressed air users have little accurate information on how their system is performing. He identifies the proper monitoring of compressed air system as a weakness in the industry.

Monitoring is important to understand the compressed air system and measuring the system over a longer period allows the creation of a baseline which includes the power and energy usage as well as specific power (kWh/m^3).

Figure18 below shows an example of a monitoring graph over a period of one week. From the graph the maximum plant demand, average consumption as well as non-productive load can be seen. A non-productive load is usually associated with leaks, such as holes in pipes, open valves or loose connections (Schutte, Kleingeld & Vosloo, 2011).

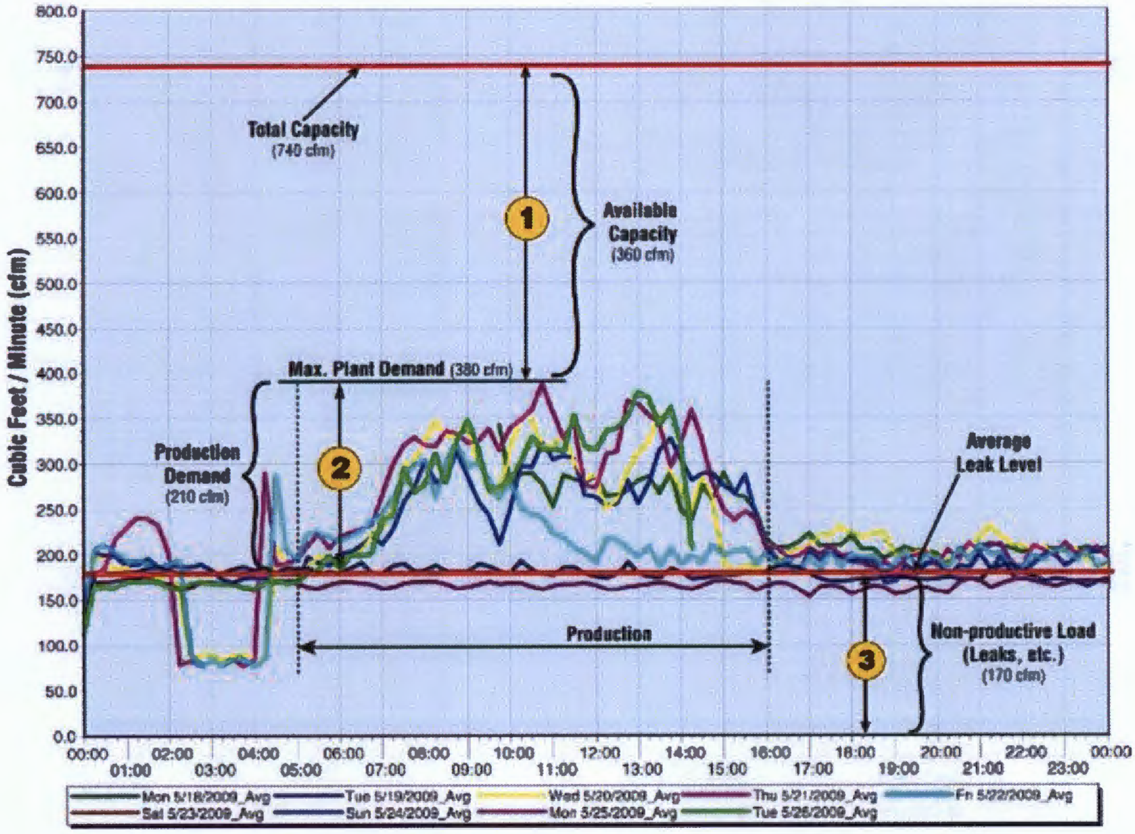

Figure 17: Compressed Air System Monitoring
(Kaeser, 2012)

2.4.6.2. Leak Prevention

Leaks contribute substantially to the wasted energy in a compressed air system. Leaks can waste 20-50% of a compressor's output and are considered the single greatest source of energy loss in compressed air systems. The cost of compressed air leaks increases exponentially, as shown in Figure 19, a tiny hole of 4mm wastes 5kW whereas a hole of 10mm already accounts for 33kW power loss (Kaya et. al, 2002). A single 4mm diameter leak will result in a financial loss of about R 30,000 per year, given that a foundry is operating for 24 hours, seven days a week.

Usually leaks occur at joints, valves, filters, hoses, connections, extensions and connected equipment. An elimination of all air leaks is practically impossible; a leakage rate of 10 - 20% is considered acceptable (Kaya et. al, 2002; Saidur, Rahim & Hasanuzzaman, 2010).

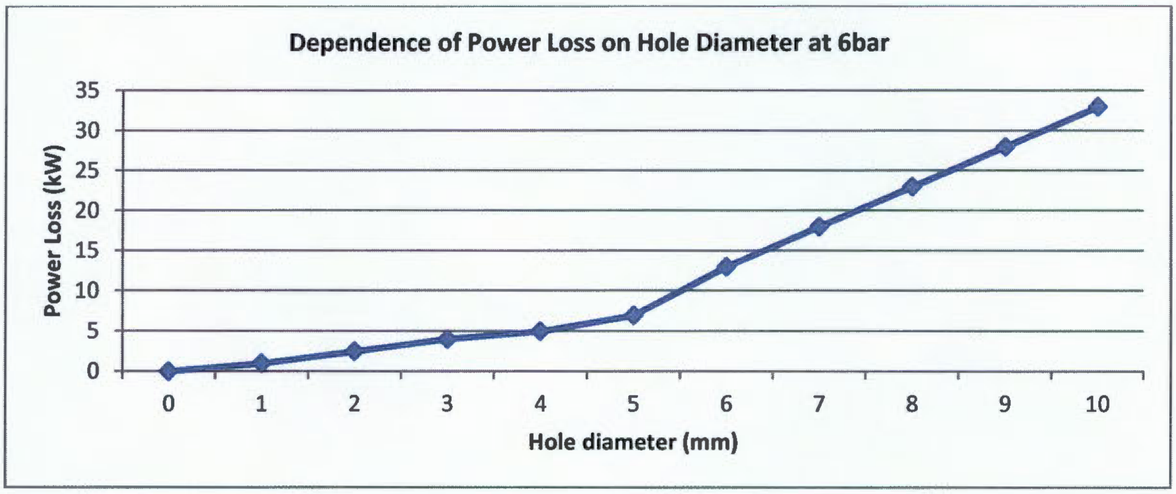

Figure 18: Power loss depending on hole diameter (6bar)
based on Kaya et. al, 2002

The cost of a compressed air leak is the energy required to compress the volume of the lost air. Given the exponential growth of leakage cost, air leaks should be repaired immediately when identified. Often leaks can be heard and located by ear; fixing can sometimes be as simple as tightening a connection or temporarily putting a clamp over the leak (Saidur, Rahim & Hasanuzzaman, 2010). The more accurate way to detect leaks is an ultrasonic acoustic detector which identifies high frequency sounds from the leaks (Abdelaziz, Saidur & Mekhilef, 2011). All air leaks should be identified and repaired during maintenance and idle time of the plant, but furthermore, air leakage detection and repair should be a continuous process. The foundry should implement a leak prevention program which includes identification, tracking, repair, verification and employee involvement (Saidur et al 2010).

By the continuous detecting and fixing of air leaks large cost savings and almost immediate payback times can be realized.

2.4.6.3. Pressure Drop

As mentioned above, compressed air systems are often oversized, therefore system pressure can be lowered in many cases without compromising the requirements. A lower pressure results in immediate saving and also minimizes the leakage rate (Abdelaziz et al, 2011).

Reducing the pressure by only 1 bar can result in about 6% increase in absorbed electricity (Eskom, 2010). Another study has found that reducing the pressure by 13 kPa will reduce the energy consumption by 1% (Galitsky, 2008).

2.4.6.4. Installing a Variable Speed Drive

Most of the compressed air systems run at partial load for long periods; they might operate at their maximum load conditions only for short periods. The result is an inefficient system and energy wastage. To increase the efficiency, the compressor capacity should be matched to the actual demand.

Motors run the most efficient at 75% or more of their rated load, below 50% of their rated load they operate inefficient. Adjusting the motor speed variably with a VSD could achieve energy savings between 15-40% and furthermore extend the motors and equipment's lifetime (Teitel et al, 2008).

However, a VSD only improves the total energy efficiency if other losses are exceeded by the benefits resulting from the VSD. If the compressor is needed to run at a steady speed for most of the time an accurately sized compressor, or possibly multiple compressors, are more efficient (Mehltretter, 2012).

2.4.6.5. Multiple Compressors

Given the fact that compressors are the most efficient near their full load, the importance of an accurate compressor sizing is clear. The efficiency of the compressed air system can be improved by using multiple compressors of different sizes, allowing them to run at their most efficient point and avoiding start-ups. Figure 19 illustrates the working principle of two equal compressors in foundry operations, where constant compressed air is needed as a base load and only during peak hours the compressed air demand is higher. Compressor 1 runs at full load very efficient constantly and no energy is lost due to regularly start-ups. Compressor 2 is sized just to meet the difference during peak demand times; therefor compressor 2 will also run efficiently at its full load.

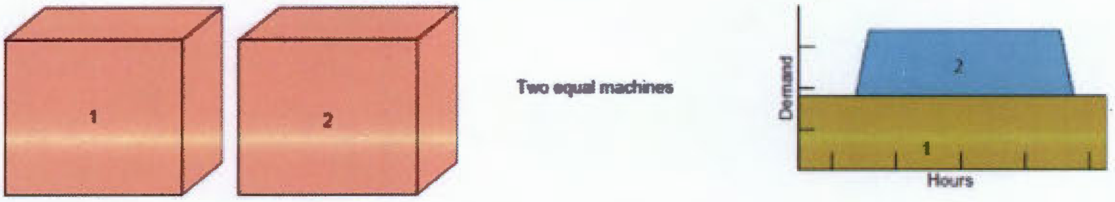

Figure 19: Compressor System with Multiple Compressors

(AMEI, no date)

2.4.6.6. Heat Recovery

Literature claims that only about 19% (Kaya et. al, 2002) of a compressor's consumed energy is actually used in the compressed air, about 80-93% of the used electrical energy is converted into heat (Saidur et al, 2010). With a well-designed heat recovery unit up to 90% of this heat could be recovered as thermal energy and used for water or space heating (Saidur et al, 2010).

The cooling air temperature of a compressor has usually about 65°C, this flue gas can be used in a recuperator, where heat exchange takes place between the cooling air and atmospheric air through metallic walls. Tubes carry the air to be preheated and the other side contains the waste heat stream. A recuperator for recovering waste heat from the compressor's cooling air is shown in Figure21 (UNEP, 2006).

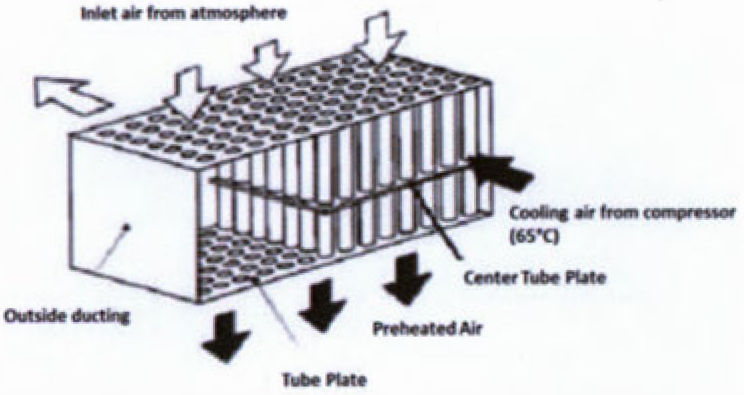

Figure 20: Heat Recovery using Recuperator adapted from (UNEP, 2006)

2.5. Summary

The background of this thesis is South Africa's energy crisis coupled with the declining economy. The industry, especially the steel and engineering industry, suffers the most from the spiking energy prices and rolling blackouts. Hence the Department of Energy has requested information on energy efficiency measures as well as fuel switching possibilities to reduce the shortage of electricity supply.

After the foundry sector in South Africa was reviewed, the actual foundry process was described in detail and broken down in three particular steps; the moulding and core making, melting process and the actual casting.

The main energy consumers were identified to be the furnace itself, heat treatment, core making and heating, but also lighting, cooling and compressors cumulatively account for a significant electricity usage. It was found that most international research and studies have identified a similar share of the energy usage in a foundry. While only one South African study on the energy usage could be identified, the specific power consumption for induction furnaces shows some variance in the international studies, where the average lies between 620 – 796 kWh/ton with a best practice minimum of 538 kWh/ton. The South African average lies according to SAFI's at 859 kWh/ton, however, it was not specified what kind of furnaces were reviewed in the survey. It is assumed that a mix of different furnaces was reviewed, as different foundries in South Africa were questioned.

From reviewed energy consumption patterns the literature was researched for energy efficiency and fuel switching opportunities for the South African foundry industry. There was no literature, studies, research or surveys, on South African energy efficiency measures in foundries. Hence most of the literature reviewed was from international research studies and best-practice guidelines. South African research was only found for overlapping interventions used in all kind of industries, such as lighting and compressed air.

The international literature has identified melting operations, fans and pumps, lighting and compressed air, the areas of highest saving potential.

Therefore, approaching the following case study assumes these areas to be potential saving areas as well.

3. Methodology

This chapter explains how the analysis of the case study was done. The approach and the underlying assumptions is explained while linking them with previously explored literature.

The nature of this thesis is the description, evaluation and exploration of energy optimization possibilities in a South African steel foundry. A case study of a foundry operating an induction furnace in the Western Cape was examined. The aim was to identify the energy intensity, evaluate already implemented energy efficiency measures and identify further opportunities to reduce energy cost.

The chosen approach was quantitative, as it fits the objective of identifying energy saving opportunities by quantifying actual consumption and finding possible focus areas. The data collected was from electricity bills, actual meter readings and past recordings of energy consumption.

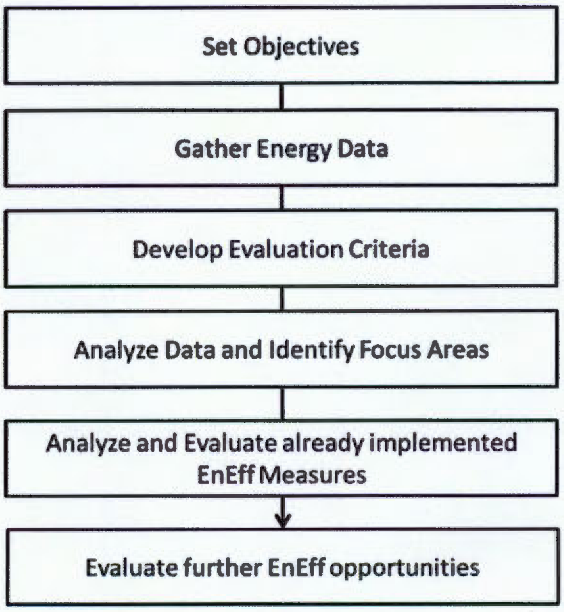

Figure 21: Methodical Approach

3.1. Energy Audit

The data collection was much orientated on an industry energy audit. An energy audit is an inspection which examines how energy is currently used in a system. The audit itself is a systematic approach to analyse energy usage, while the aim is to identify the types, amount and cost of energy usage. Furthermore, an audit will pin-point and analyse opportunities to reduce energy input without negatively affecting the production output. These energy efficiency opportunities were evaluated with an economic analysis to determine the most cost-effective options (Capehart, Turner & Kennedy, 2013).

There are three types of energy audits: the preliminary audit, general audit and detailed audit. For the purpose of this thesis the preliminary and general audit are chosen, where required a detailed audit was executed.

In a first meeting with the Energy Manager of the foundry an insight of the operation and energy consumption on site was gained. Data and information was collected for the current and historical energy consumption. The foundation for the further data collection and analysis are necessary and was given by electricity bills, recorded measurements and readings, technical drawings of the plant and documentation on already implemented energy efficiency measures.

This preliminary analysis led to the identification of the overall energy consumption, energy and production profile as well as an approximation on energy allocation by area.

On a second site visit, a walkthrough and more detailed energy audit was arranged. The purpose of the second site visit was specifically to look at previously identified focus areas, given the literature review, Figure 8 and Figure 10, and focus areas expected were the melting and holding furnaces, maximum demand, compressed air systems and lighting. This procedure, together with data from the previous stage, led to the determination of energy saving potentials and identification of the already implemented measures to evaluate.

In a third and final stage, a thorough energy audit was examined, which involves the on-site measurements and examination of the focus areas. Measured data and previously obtained historical data allowed a detailed techno-economical evaluation of energy saving measures.

3.2. Energy Consumption and Costs

For an overview of electricity consumption, maximum demand and electricity cost, all the municipal electricity bills for the audit period as well as for the last years were collected. The focus for energy consumption and cost as well as specific energy consumption was on the last full calendar year, in this case 2014. A graph was plotted and analysed to illustrate the monthly electricity consumption as well as the maximum demand trend.
From the bills, which form part of the data, the total electricity cost was calculated, and given the various time-of-use tariffs as explained in the literature review, an average electricity unit price (AUP) was estimated.

$$\mathrm{AUP} = \frac{Annual\ Electricity\ Cost\ (ZAR)}{Annual\ Electricity\ Consumption\ (kWh)} \qquad \text{Eq. (3.2.1)}$$

This average unit price was used for simplification in further energy saving calculations and evaluations.

Furthermore a regression analysis examined the correlation between production output and electricity consumption. The regression analysis is a statistical tool which compares a relationship between dependent and independent variables. The analysis attempts to explain the changes of the dependent variables as a function of the independent variables. In this context the energy consumption is the dependent variable and production output the independent variable (Arasu & Rogers, 2009).

As literature suggests, South Africa has the highest energy intensity in the BRICS countries with 1860 ZAR/ton. In order to compare the energy performance of the studied foundry the energy intensity (EI), the cost for energy per unit output, as well as specific energy consumption (SEC), the quantity of energy required per unit output, was estimated as followed:

$$\mathrm{SEC} = \frac{\text{Annual Consumption (kWh)}}{\text{Annual Net Production (tonnes)}} \qquad \text{Eq. (3.2.2)}$$

and

$$\mathrm{EI} = \frac{\text{Annual Electricity Cost (ZAR)}}{\text{Annual Net Production (tonnes)}} \qquad \text{Eq. (3.2.3)}$$

In a further step the power consumption rate for the induction furnaces was calculated. Having obtained measurements of the power consumption of the induction furnaces as well as production data of total gross tonnes the specific power consumption rate of the induction furnace (SEC_F) was calculated as follows:

$$SEC_F = \frac{\mathit{Annual\ Consumption}\ \text{of Furnace}\ (kWh)}{\mathit{Annual}\ \text{Gross}\ \mathit{Production}\ (tonnes)} \qquad \text{Eq. (3.2.4)}$$

and knowing the theoretical energy requirement (Q_{th}) with Eq. (2.4.1), the efficiency (η) was calculated with:

$$\eta = \frac{Q_{th}}{SEC_F} * 100 \qquad \text{Eq. (3.2.5)}$$

3.3. Consumption by Electricity Usage Area

This particular step required the further investigation of areas using energy within the facility. This was done through existing metering, specific measuring and through estimations. Based on the identified energy consumers in a foundry in the literature review, these categories were examined.

Some metering data was available for specific areas, such as the moulding line, machining area, dust extraction, etc. For the induction furnace a specific meter was available which showed the specific energy usage of the furnaces.

The compressed air system was examined together with the company CS Air Services (Pty) Ltd. over a period of one week, including the weekend. From a detailed audit the energy demand as well as the maximum compressed air plant demand, average air consumption and non-productive load was obtained. The energy consumption therefore was measured by means of a clamp-on ammeter, while the air flow will was measured with a modern flow meter, according to the calorimetric measuring principle, provided by CS Air Services Pty Ltd. Traditionally the no-load test was used to estimate the leakage rate of a compressed air system. For this method the total system volume size including any downstream air receivers, piping are required, which can be difficult to acquire. The use of modern flow meters therefore guarantees an easier and more accurate method to measure the leakage rate (Blessing, 2014).

For other significant energy users the electricity consumption was estimated using a "bottom-up" approach. Bottom-up models are models that use input data of the equipment and model the electricity consumption accordingly. In particular the engineering bottom-up model estimates the energy consumption by taking into account energy ratings, for example from name plates and hours of usage (Larsen & Nesbakken, 2004). It was found that the lighting and the electric motors have no specific meter; hence lighting or motor count respectively, coupled with the nominal power rating and operating hours the annual electricity consumption was estimated.

In order to illustrate the energy flows accordingly, the breakdown of all the energy usages by area was then plotted in a Sankey diagram. In these diagrams energy in- and outflows are represented quantitatively and in proportion to the total energy input according to the electricity bills (Schmidt, 2008).

3.4. Evaluation Criteria

The energy efficiency measures were evaluated related to energy, environmental as well as economic criteria. Furthermore financing options were taken into account for the economic evaluation. The following criteria are based on the Energy Audit Guide from Malamatenios (2000):

Energy Criteria

Criteria which was taken into account regarding the energy aspects included:

- Quantity of electricity saved in kWh
- Quantity of demand reduced in kW
- Annual economic profit due to energy savings or fuel switching

Economic and Financial Criteria

Criteria which was taken into account regarding the economic and financial aspects included:

- Initial capital required for intervention
- Economic performance of investment, which represents the annual profit due to energy cost savings
- Funding or financing possibilities

Environmental Criteria

Criteria which was taken into account regarding the environmental aspects included:

- Annual reduction of carbon emissions in tonnes
- Possibly any other environmental issues, such as water usage, waste reduction

3.5. Analysis of Energy Efficiency Measures

3.5.1. Lighting

The electrical consumption was compared and evaluated by the above criteria before and after installation of the new lighting equipment. The annual electricity consumption (AEC_L) of the old and respectively the new lighting system was estimated by earlier introduced "bottom-up" approach with following Eq. 3.5.1.1. The annual electricity savings (AES_S) were in turn estimated as the difference of the both systems.

$$AEC_L = \sum_{i=1}^{n,m}(P_1 * n_1 * hr_1 + P_2 * n_2 * hr_2 + \cdots + P_m * n_m * hr_m)$$ Eq. (3.5.1.1)

$$AES_L = AEC_{L,old} - AEC_{L,new}$$ Eq. (3.5.1.2)

Annual bill savings associated with above energy savings were calculated with:

$$Savings = AES_L * AUP_a$$ Eq. (3.5.1.3)

with

P_m = power rating of light bulb [kW]

n_m = count of specific light bulb

hr_m = annual running hours

AUP_a = average unit price of specific year [ZAR/kWh]

Furthermore, the simple payback period for the energy efficient intervention was calculated using Eq. 3.5.1.4. As previously mentioned there was public funding available, in which case the amount of funding reduced the incremental cost.

$$Simple\ payback\ years = \frac{Incremental\ Cost\ (ZAR)}{Savings\ (\frac{ZAR}{year})}$$ Eq. (3.5.1.4)

As the energy saving reduces the electricity generation from Eskom power plants consequently the carbon emissions will be reduced as well. The amount of emissions reduced in a year was estimated with the above annual electricity savings and the specific emission factor (EF= 0.909 tCO2/MWh) for South Africa (Spalding-Fecher, 2011).

$$Emission\ Reduction = AES_L * EF$$ Eq. (3.5.1.5)

3.5.2. Load Shifting

For the evaluation of the load shifting implementation, the electricity consumption profile and associated electricity cost before and after implementation were compared. The historic metering data in an hourly interval was plotted together with the current hourly energy consumption.

Data was obtained from the past pulse meter recordings and the newly installed Padicon® system, which both recorded the kW demand on an hourly basis.

To compare results, the consumption before load shifting was extrapolated to match the total consumption after installation. A consumption factor (CF) was calculated as the ratio of the before and after values of consumption. The hourly distribution remained the same, but cost savings were estimated due to the load shifting.

The savings were therefore estimated with following:

$$Consumption\ Factor\ (CF) = \frac{Total\ Consumption\ Before\ (kWh)}{Total\ Consumption\ After\ (kWh)}$$ Eq. (3.5.2.1)

$$Extrapolated\ Consumption\ (p) = X_p * CF$$ Eq. (3.5.2.2)

$$Cost = \sum_{p=1} X_p * C_p$$ Eq. (3.5.2.3)

where

CF = Consumption Factor

X_p= Consumption in specifc period (off-peak, standard, peak) [kWh]

C_p= Cost in specific period [ZAR/kWh]

And the monthly cost savings were estimated with:

$$Savings = (Cost\ Before - Cost\ After) * days\ of\ month$$ Eq. (3.5.2.4)

3.5.3. Maximum Demand

In order to review the result of an implemented demand control, the maximum demand before and after installation as well as the cost induced by it, was compared.

Given the historic pulse meter which recorded kVA demand as well as the new Padicon® system guaranteed accurate data to plot and analyse the results. For visual comparison a demand bar chart was plotted, to identify the difference of any demand spikes.

Further the maximum demand before the installation and after the installation was identified on which the actual reduced maximum demand and caused cost benefits were estimated with:

$$Max\ Demand\ Saving = Max.Demand\ Before\ (kVA) - Max.Demand\ After(kVA)$$

Eq. (3.5.3.1)

$$Savings = Max\ Demand\ Saving\ (kVA) * Max\ Demand\ Charge\left(\frac{ZAR}{kVA}\right)$$

Eq. (3.5.3.2)

While the economic criteria will be analysed with the simple payback method:

$$Simple\ payback\ years = \frac{Investment\ Cost\ (ZAR)}{Savings\ \left(\frac{ZAR}{year}\right)}$$

Eq. (3.5.3.3)

3.6. Theoretical Analysis of Energy Efficiency Recommendations

3.6.1. Preheating of Charge Material

The energy and cost saving of preheated charge material was estimated by the difference of the theoretical energy consumption (Q_{th}), the energy required to heat up one ton of charge material to tapping temperature, and the energy consumption (Q_{pre}), the energy required to heat up one ton of 450°C preheated charge material to tapping temperature. Therefore following equations were used:

Energy Criteria

$$Q_{th} = Q_m + Q_{sh} + Q_s \qquad \text{Eq. (2.4.2)}$$

$$Q_{pre} = Q_{mpre} + Q_{sh} + Q_s \qquad \text{Eq. (3.6.1.1)}$$

where

$$Q_{mpre} = MC(\theta_1 - \theta_{T(t)}) + ML \qquad \text{Eq. (3.6.1.2)}$$

and

$$Q_{sh} = MC_m\theta_{sh} \qquad \text{Eq. (2.4.4)}$$

$$Q_s = K_sG_s \qquad \text{Eq. (2.4.5)}$$

With

M = mass of charge (1 ton)

c = specific heat capacity of charge, (for cast iron C = 792 J/kg K)*

c_m = average heat capacity of molten steel (C = 700 J/kg K)*

L = latent heat of fusion of steel, (for cast iron C = 272 J/kg K)**

θ_1 = melting temperature of charge (1400°C)***

θ_0 = initial charge temperature (ambient temperature, 25°C)***

θ_{sh} = amount of superheat temperature (50°C) ***

$\theta_{T(t)}$ = preheated temperature after transport to induction furnace (see below calculation)

K_s = quantity of slag formed (average 8% of furnace capacity in ton)**

G_s = heat energy of slag (1800 J/kg K) **

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* http://www.pyrometallurgy.co.za/MoltenSlags2012/W126.pdf

** Mansoor & Shahid 2014

*** provided by foundry staff

As the preheated charge material will lose energy during transport to the induction furnace, the temperature loss was estimated with Newton's law:

$$T(t) = T_A + (T_{pre} - T_A)e^{-kt} \quad \text{Eq. (3.6.1.3)}$$

where

T_A = ambient temperature (25°C)***

T_{pre} = preheated temperature (450°C)

k = 0.056

t = time (min)

As the calculated energy consumptions are represented in Joules they were converted in kWh and the electricity saving per ton (ES_{pre}) was calculated with:

$$ES_{pre} = Q_{th} - Q_{pre} \quad \text{Eq. (3.6.1.4)}$$

and annual cost savings (ACS_{pre}) are the multiplication of electricity savings with the average electricity price and annual total production:

$$ACS_{pre} = ES_{pre} * AUP * ATP \quad \text{Eq. (3.6.1.5)}$$

To estimate the total savings, the cost of the gas required was subtracted from the electricity savings. For the estimation of gas required the energy necessary to heat up the charge material to 450°C was calculated with (for simplification a 100% gas utilization factor is assumed):

$$Q_{gas\,pre} = MC(\theta_{450} - \theta_0) \quad \text{Eq. (3.6.1.6)}$$

Knowing the required gas energy($Q_{gas\,pre}$), the gas usage in kg (GU) to heat up one ton of charge material was estimated given the calorific value (cv_{gas} = 49.6 MJ/kg) of LPG (Afrox, 2005)

$$GU = \frac{Q_{gas\,pre}}{CV_{gas}}$$ Eq. (3.6.1.7)

and annual gas expenses (AGE) hence was estimated with the gas price (GP), annual total production (ATP) with Eq. 3.6.1.8:

$$AGE = GU * ATP * GP$$ Eq. (3.6.1.8)

therefore the total annual cost savings (ACS) of the preheating system are

$$ACS = AES_{pre} - AGE$$ Eq. (3.6.1.9)

Economic Criteria

Since the addition of the gas preheating system is a fuel switching intervention, the actual cost saving is dependent on the cost structure of gas and electricity. Hence the electricity savings and gas cost was modelled for a period of 5 years and plotted in a graph. The electricity price was escalated in terms of the price increase granted by NERSA, 12.69% (Creamer, 2015b) and the gas price escalation, 0.5 – 3%, was used by recommendation of the International Monetary Fund (IMF, 2015).

Further, as the price escalation, especially of the gas price is rather unpredictable and since Eskom still applies for a further electricity price increase, a scenario analysis with following values was performed:

	Assumed Values	Gas Price Inflation Scenarios			Electricity Price Inflation Scenarios	
Changing Factors:						
gas price	3%	1%	2%	5%	3%	3%
electricity price	12.69%	12.69%	12.69%	12.69%	18.0%	25.3%

Table 4: Values for Preheating Cost Saving Scenario

Environmental Criteria

As the electricity saving reduces the carbon emissions emitted by the power generator, the amount of emissions reduced annually was estimated with before introduced Eq. 3.5.1.5.

However, in this fuel switching case, emissions from electricity might be reduced but burning LPG emits carbon emissions as well. The amount of emissions produced in a year of burning LPG was estimated with the above estimated gas consumption and the specific emission factor (EF= 0.447 tCO_2/MWh) for LPG (Letete, Guma & Marquard, 2009). Hence the actual emission reduction was estimated as followed:

$$Emission\ Reduction = AES_{pre} * EF_E - AGC * EF_{LPG} \qquad \text{Eq. (3.6.1.10)}$$

3.6.2. Compressed Air System

Energy and Economic Criteria

As previously discussed the compressed air system was monitored with a clamp-on ammeter while the air flow was measured with a modern flow meter. From the monitoring results the energy demand, as well as the maximum compressed air plant demand, average air consumption as well as non-productive load was obtained. This monitoring was done over the period of a week. The electricity consumption was extrapolated to estimate the annual electricity consumption. Further the average compressed air delivery for the measured week was also be extrapolated to estimate the total annual delivery in m^3.

Having obtained these figures, the specific power consumption as well as the average cost for compressed air was estimated as followed:

$$SEC_C = \frac{annual\ electricity\ consumption}{annual\ air\ delivered} \qquad \text{Eq. (3.6.2.1)}$$

$$AUP_C = SEC_C * AUP_a \qquad \text{Eq. (3.6.2.2)}$$

where

SEC_C = specific energy consumption compressed air [kWh/m³]

AUP_C = average unit price of compressed air [ZAR/m³]

AUP_a = electricity cost [ZAR/kWh]

The leakage rate was obtained from the monitoring measurements on a day without production, such as a Sunday. The non-productive load was then be measured and compared to the total delivered average of compressed air. As literature suggests, the non-productive load suggests leaks (Schutte, Kleingeld & Vosloo, 2011). Hence the leakage rate was estimated as followed:

$$Leake\ Rate\ (\%) = \frac{\text{non-productive load}}{\text{total delivered average}} \quad \text{Eq. (3.6.2.3)}$$

and the cost of compressed air leaks can be estimated by

$$Cost\ Leakages = \text{non} - \text{productive load} * AUP_C \quad \text{Eq. (3.6.2.4)}$$

Environmental Criteria

Given the non-productive load and knowing the specific power consumption rate SEC_C the "avoidable" emitted carbon emissions were estimated with:

$$Emissions = non - productive\ load * EF_E \quad \text{Eq. (3.6.2.5)}$$

3.6.3. Reduction of Holding Furnace

Energy and Economic Criteria

The annual electricity consumption (AEC_H) of the current holding furnaces was estimated by earlier introduced "bottom-up" approach with following Eq. 3.6.3.1.

$$AEC_H = \sum_{i=1}^{n}(P_1 * hr_1 + P_2 * hr_2 + \cdots + P_m * n_m * hr_m) \quad \text{Eq. (3.6.3.1)}$$

with

P_m = power rating of holding furnace [kW]
hr_m = annual running hour
AUP_a = average energy cost of specific year [ZAR/kWh]
n = number of holding furnace

As the holding furnaces will be replaced by a larger pouring furnace the annual electricity saving (AES) will be equal to annual electricity consumption of the holding furnaces subtracted by the consumption of the pouring furnace. The cost savings were calculated by multiplying the annual savings with the average electricity price.

$$AES = AEC_P - AEC_H \qquad \text{Eq. (3.6.3.2)}$$

$$Savings = AES * AUP_a \qquad \text{Eq. (3.6.3.3)}$$

Furthermore, the simple payback period for the energy efficient intervention can be calculated using Eq. 3.6.3.4.

$$Simple\ payback\ years = \frac{Investment\ Cost}{Annual\ Savings} \qquad \text{Eq. (3.6.3.4)}$$

Environmental Criteria

The amount of emissions reduced in a year was estimated with the before estimated annual electricity savings and the specific emission factor.

$$Emission\ Reduction = AES * EF \qquad \text{Eq. (3.6.3.5)}$$

4. Case Study – Analysis and Evaluation of Energy Efficiency Measures

4.1. Company Overview – Metal Casting Foundry

The foundry under review is located in the Western Cape and was originally erected on a Greenfield site in 1981. The company supplied automotive castings to an engine manufacturer, which was manufacturing engines for the South African commercial and agricultural market.

In 1999 the operation was acquired by a German truck manufacturer which founded two divisions, the Foundry and the Machining Facility. The foundry manufactures cast grey iron cylinder blocks ranging from 55kg to 575kg as well as machined commercial vehicle diesel engine blocks ranging from 4 to 12 cylinders. In 2012 an additional fourth induction furnace with a 10-tonne capacity was added to increase the melting output, following which, the foundry had a first record year of 60,000 tonnes of cast produced. Since last year the output was further increased, producing almost 70,000 tonnes of cast annually.

The foundry is the one of the largest electricity consumers connected to the City of Cape Town grid, with a maximum demand of 26.5MVA and consuming about 130,000 MWh annually. The operation is looking to further increase its production capacity; therefore a number of projects are underway to install new machinery. These projects include, for example, a new sand drying plant and a new melting furnace power pack (6.1MW). Currently there are only three power packs available for the four induction furnaces, resulting in a reduced output for the two furnaces sharing one power pack. Due to the supply constraint the operation cannot request additional power from the municipality without major cost. An alternative solution could be the installation of own power production or reduction of the current load to accommodate the new equipment.

4.2. Manufacturing Process

The manufacturing process of the engine blocks is split into three distinctive sections, namely (I) Core Making, (II) Green Sand Plant and (III) Melting Plant, the detailed operation of these sections is similar to the previously described section 2.2 Foundry Process. The actual manufacturing process is shown in Figure23. This case study will focus on the energy consumption patterns and energy efficiency opportunities of the core making and melting section.

In (I) the Core Making section the cores for the engine blocks are manufactured in a heated process. Dried sand is placed in the core shooter, which makes use of compressed air and hydraulics to compress the sand into a specific shape. The core is eventually coated with a chemical and dried in a stoving process.

The (II) Green Sand Plant manufactures the moulds out of sand, as described in chapter 2.2.1. The foundry manufactures lost moulds, where for each casting a mould gets made and destroyed after the pouring. The moulds are made out of sand, whereby sand is mixed with clay and water and then packed or rammed around the pattern to form the mould. This operation makes use of a significant amount of compressed air and hydraulics.

The (III) Melting Plant makes use of four core type induction furnaces each with a 6.1 MW capacity and several holding vessels. The melting plant incorporates three power packs each 6.1 MW, while two are exclusively for furnace 3 and 4, and the other power pack is shared between furnace 1 and 2.

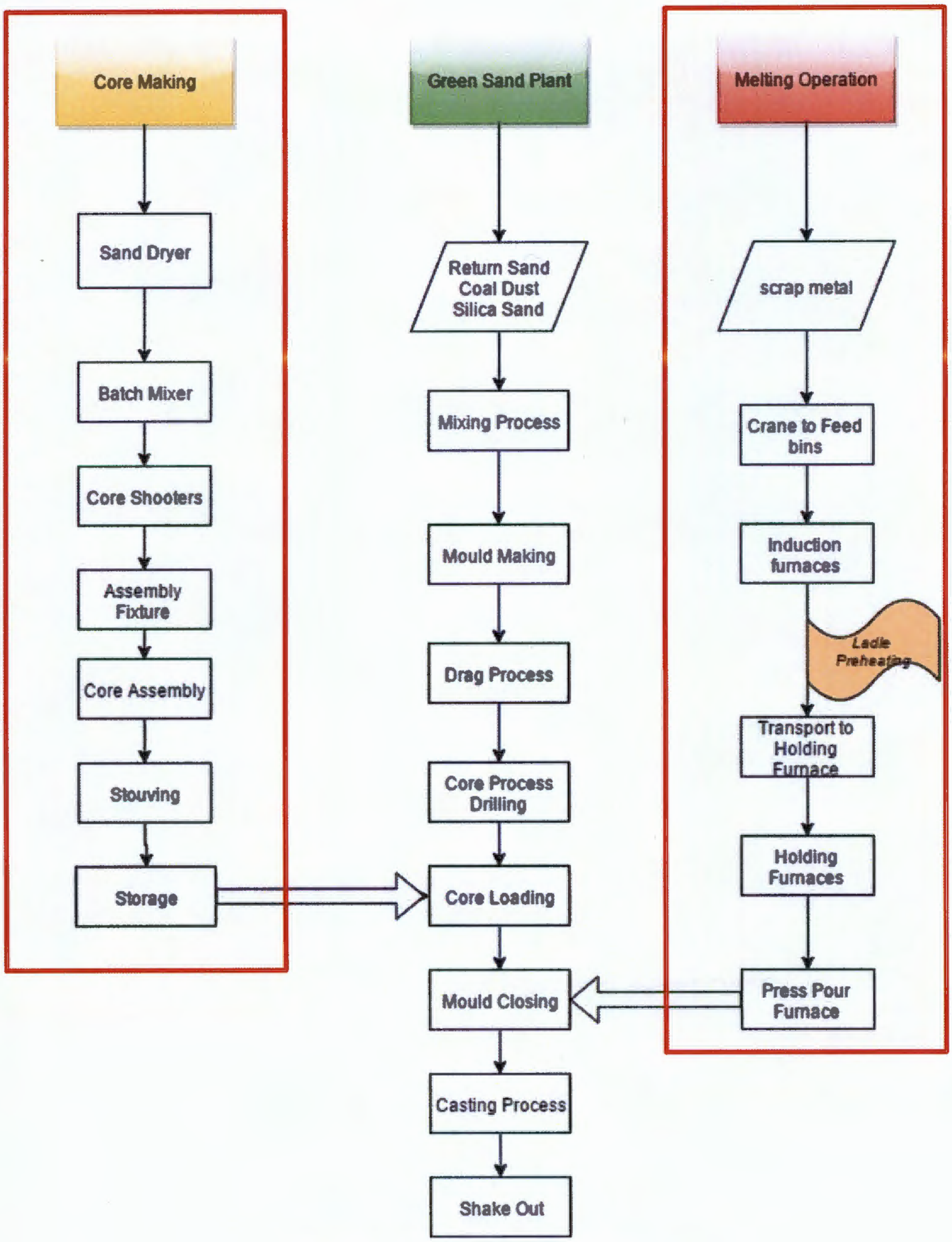

Figure 22: Overview of Manufacturing Process

4.3. Energy Consumption and Costs

4.3.1. Energy Consumption

From electricity bills provided, the total annual electricity usage from 2014 was calculated to be 127,099MWh with a maximum demand of 26.5MVA. Figure24 below shows the electricity consumption and demand of 2014. Evidently there is less electricity consumption in January 2014 and December 2014; this is due to the holiday season and closure of the foundry. Notably however, the maximum demand in January 2014 is only 23,520kVA and February 2014 25,5000kVA compared to the other months were the maximum demand is constant on about 26,500kVA. The reason for that is the (later discussed) maximum demand control unit. Before March 2014 the foundry was running on a maximum of 23,500kVA while it increased its maximum demand limit to 26,500 due to increased production demand.

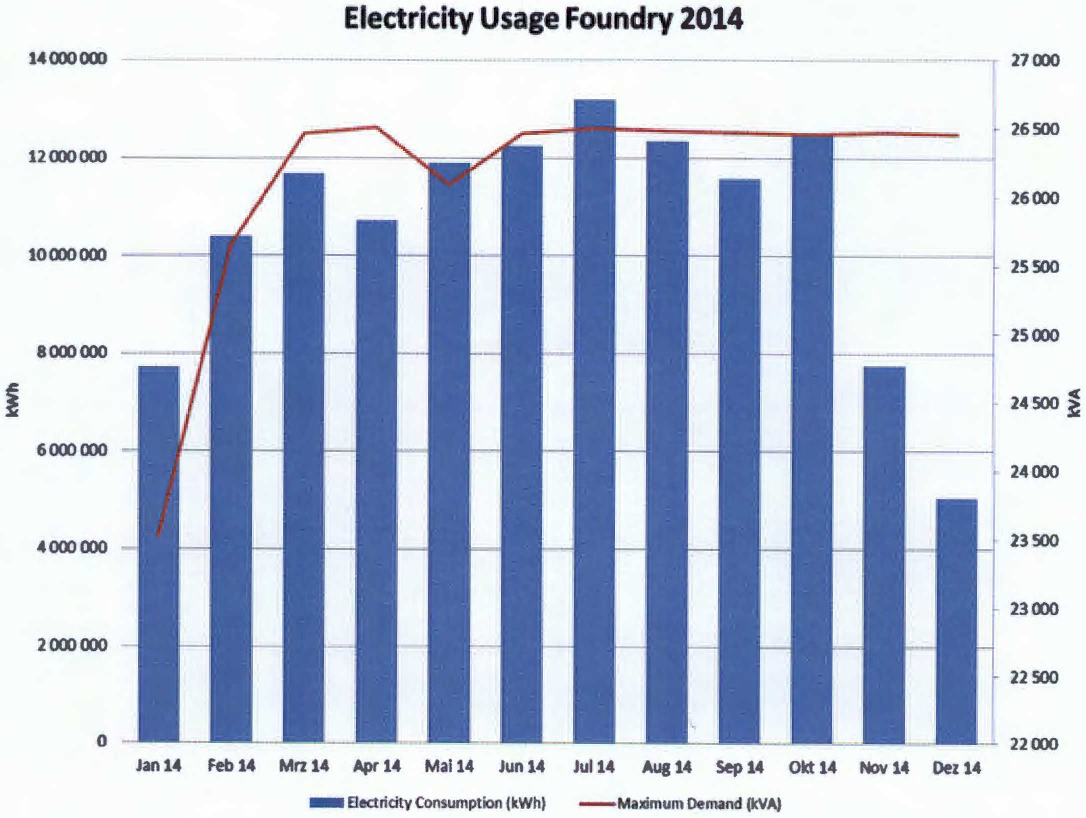

Figure 23: Electricity Consumption Foundry

In order to determine the correlation between the electricity consumption and the production output, a regression analysis was performed. In the regression analysis the monthly production output (in tonnes) represents the independent variable, whereas the electricity consumption (in terms of kWh) the dependent variable. Figure 25 indicates the relationship between the two factors and it is observed that the model gives a positive correlation between production output and electricity consumption, given a high $R^2 = 0.88$. Furthermore Eq. 4.3.1 indicates that about 2,000,000 kWh are consumed even if there is no production at all (if x=0). This equation is a useful tool to predict energy consumption according to the production rate.

$$y = 1566.5x + 2{,}000{,}000 \qquad \text{Eq. (4.3.1)}$$

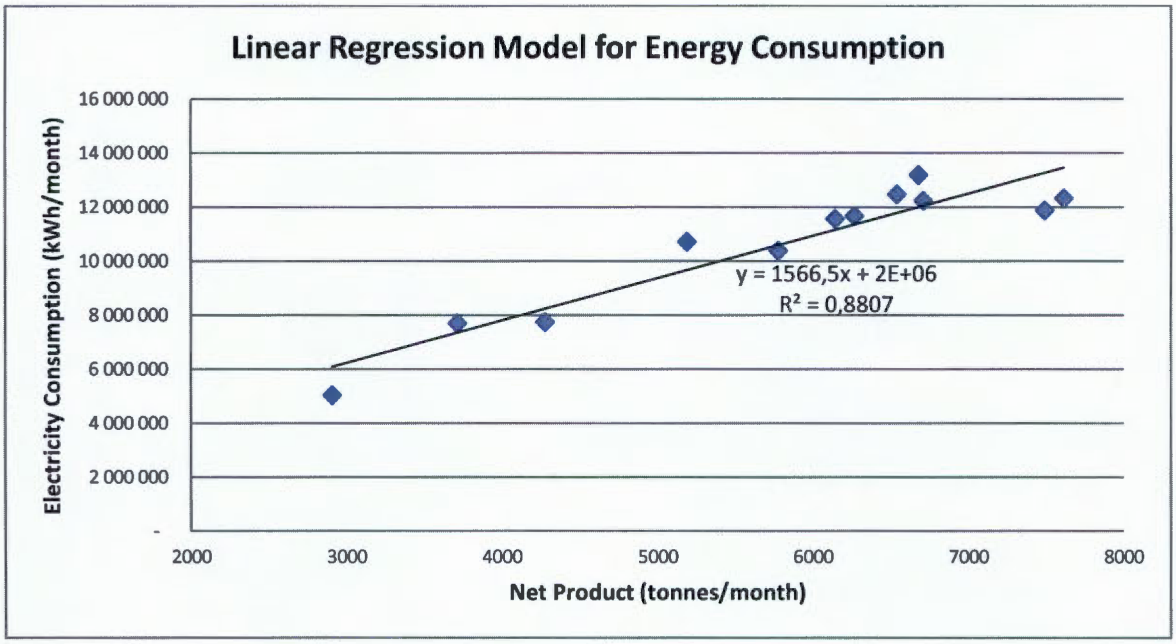

Figure 24: Linear Regression Model for Energy Consumption

Having established the positive correlation of electricity consumption and production in tonnes, the specific power consumption of the induction furnaces was estimated, given the gross production output, the melted metal amount, and the electricity consumption of all four furnaces combined, to be 621kWh/ton. Knowing Eq. 2.5.6 and calculating theoretical energy requirement

(Q_{th}) the energy efficiency (η) of the four furnaces combined is 50.4%. Comparing the specific power consumption with literature shows that the efficiency lies within the suggested range. Furthermore 621kWh/ton lies below the South African average of 859kWh/ton but within the same level as the Indian average (Arasu & Rogers, 2009). The research done by UNIDO (1998) also confirms the specific power consumption to be within the range of a 10-ton induction furnace.

The underlying calculation of the foundry under review entails some uncertainty though, as the specific power consumption represents the average of all four induction furnaces, as no measurements for a single furnace were available.

From the total electricity consumption per month, and having obtained measurements at different meters in the factory, a Sankey diagram was created to show the flow of electricity within the foundry. As expected and suggested by literature, the four induction furnaces use, with 44% of the total consumption, most of the electricity. The moulding and green sand plant use their electricity with heat treatment, electric machines and tools as well as coating. Next to the melting operation the electric motors were identified as the second largest electricity user accounting to 12% of total consumption, followed by holding furnaces accounting to 10%. The specific usage is shown in Figure26 in the form of a Sankey diagram. As it was not possible to measure all electricity consumers accurately some consumption values were estimated, the variable "unaccounted", is to match up with the actual total consumption provided by the electricity bills.
Furthermore, due to confidentiality reasons the amount and cost of gas supply could not be analysed.

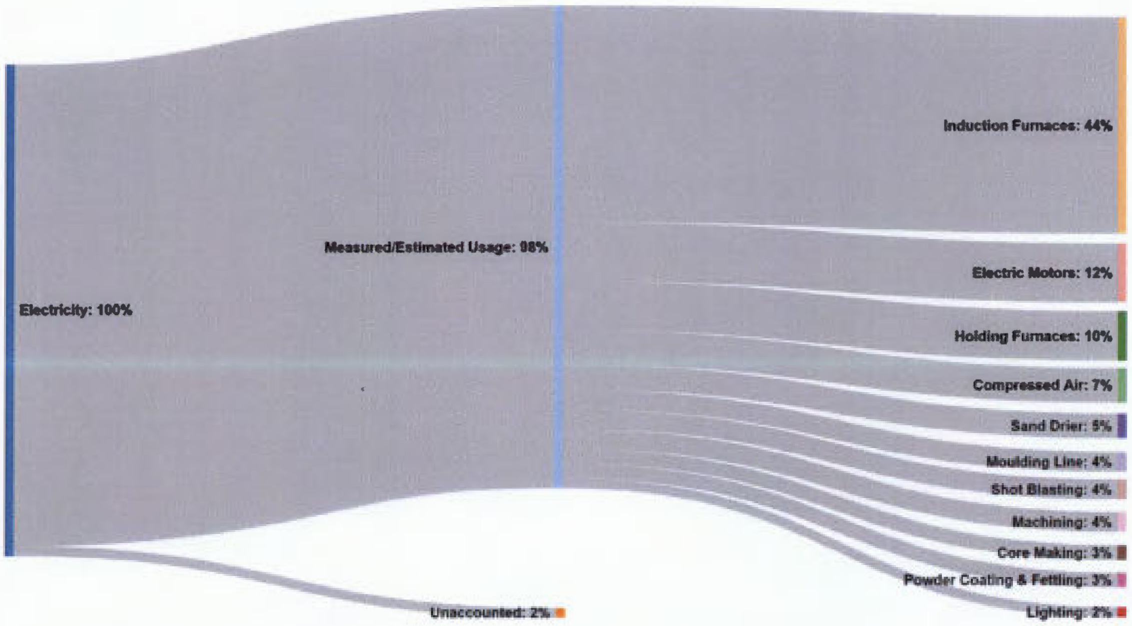

Figure 25: Sankey Diagram Foundry

4.3.2. Energy Cost

The company is supplied with electricity from the City of Cape Town municipality. The plant currently runs on the City's medium voltage time-of-use tariff, which charges the customer according to the time of electricity consumption and is split into daily peak periods as well as seasonal pricing. The time-of-day usage is split into three periods, with peak time (weekdays 07h00 – 10h00 and 18h00 - 20h00), standard periods (06h00 – 07h00, 10h00 – 18h00 and 20h00 – 22h00) as well as off-peak periods (all other times). Further to the time of day usage there is a differentiation in seasonal usage. These tariffs are higher in the winter period (June to August) than in summer periods (September to May). As the company is located in an industrial hub, the city of Cape Town offers a 10% incentive scheme on the electricity price (City of Cape Town). Table 5 below shows the tariff structure of the foundry from the last three years highlighting the price increase.

Energy Costing Foundry				
Energy Parameter	**Unit**	**2013/14 excl. VAT**	**2014/15 excl. VAT**	**2015/16 excl. VAT**
Service Charge	R/day	5210	5500	6090
Energy Charge: High Demand (June to August)				
Peak	R/kWh	2.55	2.46	2.72
Standard	R/kWh	0.68	0.71	0.79
Off Peak	R/kWh	0.37	0.39	0.44
Energy Charge: Low Demand (September to May)				
Peak	R/kWh	0.73	0.77	0.85
Standard	R/kWh	0.45	0.51	0.58
Off Peak	R/kWh	0.32	0.34	0.39
Demand Charge	R/kVA	81.03	84.21	93.30
LPG cost[5]	R/kg	12.8	12.8	12.8

Table 5: Energy Costs Foundry (City of Cape Town)

Due to the different time-of-use tariff and mid-year price increases, an average price for one unit of electricity was calculated for simplification. Given the total electricity demand and a total cost of ZAR 103,082,325 in 2014, an average electricity price of 0.81 ZAR/kWh was determined. For further evaluations and feasibility calculations the average electricity price for 2015 and the following years was modelled, given the price increase of 12.69%. The latter is shown in Table 6 below.

	average 2014	average 2015	average 2016	average 2017	average 2018
ZAR/kWh	0.81	0.91	1.03	1.16	1.31

Table 6: Average Electricity Price Prediction Foundry

Given the average electricity price and previously established relationship between production output and energy consumption, the energy usage of 2014 was calculated to be 1,853 kWh/ton which results in an energy intensity of 1,493 ZAR/ton. Therefore it can be concluded that the overall energy utilisation of the company is within the good performers. The study of SAIF has

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[5] Estimated LPG price as real price confidential

shown that the average price of produced casting ton in South Africa lies at about 1860 ZAR/ton[6] (Mitchell, 2013).

4.4. Review of Implemented Energy Efficiency Measures

Since the power crisis in 2008, the South African industry experienced a steep increase in prices, and to overcome supply constraints Eskom implemented demand side management (DSM) programmes. The company under review also implemented a number of projects and thereby benefited from incentives from the government. Since 2011 the overall energy intensity has already improved by almost 90kWh/t from then 1,921kWh/ton due to some interventions. In the following chapters implemented energy efficiency measures by the foundry are reviewed and evaluated.

4.4.1. Lighting

Reviewed literature states that optimizing lighting is a "low-hanging" fruit, an easy measure to achieve energy savings. The foundry under review has done a lighting project to save power as one of their first energy efficiency projects in the end of 2011 and a further one in 2012.

In 2011 the foundry was using about 3,700,000 kWh for lighting and was approached by an energy efficiency project developer to reduce their energy cost. The project developer made use of the Performance Contracting model of Eskom's demand side management programme.
Performance Contracting had the requirement that at least 30,000 kWh savings in a three year period were achieved. The project developer was responsible for all the capital cost incurred and Eskom reimbursed him by the measured and verified savings (Eskom, 2012). Hence, the foundry had no capital cost for the first retrofitting of their lighting.

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[6] given currency exchange rate 13/07/2015, USD/ZAR 12.41

The project included the conversion of 400W mercury vapour high bay lights to 200W mercury halide lights. In total 282 lights were changed in the machining and fettling section, as these lights are turned on for 24 hours each day the retrofit resulted in a saving of almost 500,000kWh annually. There were no lights changed in the foundry section, as the furnaces could not be turned off during the time and working was rated to be too dangerous.

In a later stage, the company replaced its lights in the foundry section and made use of the Standard Product Offer from Eskom's integrated demand management programme. The Standard Product programme provided specific rebates for efficiency improvements derived from the implementation of approved technologies such as lighting. The requirement was that customers save energy of maximum 250kW but with at least 2 MWh per annum. Depending on the technology Eskom incentivises the customer with 0.42-0.70ZAR per saved kWh. The specific rate for LED technology is 0.55 ZAR per kWh saved (Eskom, 2012).
The foundry replaced 666 of 400W mercury vapour lamps with 479 of 100W LED Highbay lamps and with 135 of 50W LED Highbay lamps. The lights will thus save 211kW, equivalent to 1,650MWh per annum. This is equivalent to about 1,000,000ZAR per annum at 2012 tariffs. The Eskom programme for LED interventions resulted in the rebate subsidizing approximately 47% of 1,900,000ZAR total project costs; hence a payback of less than one year was achieved.

Overall both lighting projects reduced the lighting specific electricity consumption by 56% and had each less than a year payback times. Furthermore the lighting level has been found to be between 800-1000 lumen/m^2, which the literature mentioned as the optimal lighting level (Whiting, 2001). Combined, the new lighting system reduced the carbon emissions by 1,950 tCO$_2$ per year.
Coming back to the energy usage (kWh/ton), the lighting project reduced the consumption of 1,921kWh/ton by 37 kWh. Hence it can be concluded that the both lighting projects were successful and added positively to the company's energy efficiency.

4.4.2. Maximum Demand Control

The demand charge, which is determined by the monthly maximum demand, has a direct influence on the energy bill. Prior to 2012 the foundry did not have a demand control system, resulting in fluctuating demand with uncontrolled high peaks and unnecessary high cost.

Overstepping the anticipated demand of 23,500 kVA by 4,900kVA, it cost the company about 445,900 ZAR in June 2011. In order to regulate the maximum demand the foundry installed a power control system in March 2012 called Padicon® from Dr. Tannenberger GmbH. As described in the literature review, the parallel-difference-power control, controls the power supply to the furnaces in a smooth manner and therefore reduces the demand simultaneously. Figure 27 shows compared demands from June 2011 and August 2012 after successful installation of the demand control.

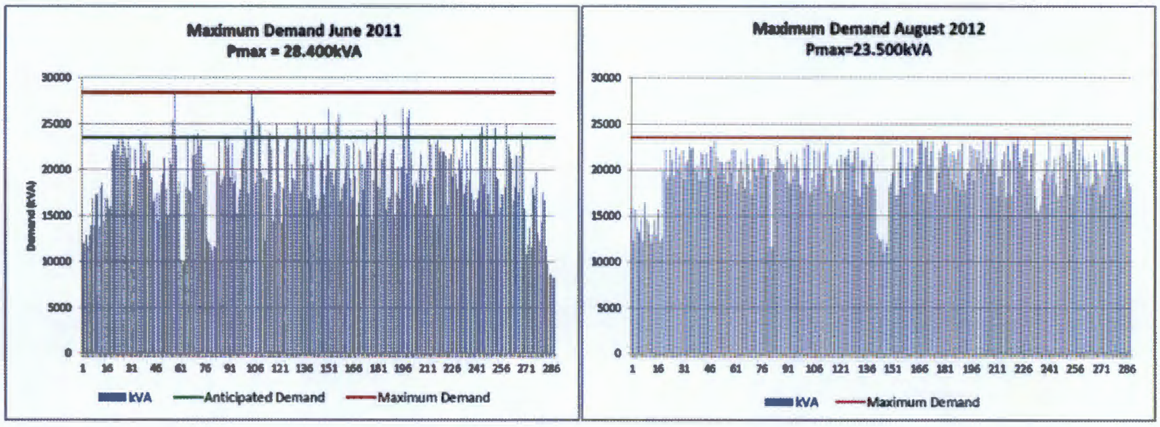

Figure 26: Maximum Demand Comparison

As the direct comparisons of the two graphs show, the elimination of the demand peaks resulted in a cut of 20.8% of the maximum demand. The load was permanently reduced by about 3,000 kVA and kept on a maximum of 23,500 kVA which saved the foundry on average 270,000 ZAR monthly. Taking into account that the investment cost of the Padicon® was 3,000,000 ZAR the installation showed a return already after less than one year.

4.4.3. Load Shifting

As mentioned previously, the foundry is charged by the time-of-use tariff which has a large price difference between peak and off-peak periods, ranging from the highest about R2.7/kWh and the lowest R0.4/kWh. This large difference in electricity tariffs has moved the company under review to also shift their production and electricity consumption accordingly. The focus of the operating schedules was on the furnaces as they are by far the largest electricity consumers. The installed Padicon® system is also able to manage the furnaces given a certain schedule. As the production output increased in any case, some production also had to be added to the night shifts.

The loads of a normal production day in February 2012 (before the installation of Padicon®) and May 2015 were compared. The graph below illustrates the per hour power consumption in the given time-frame for a day in February 2012 and a day in May 2015 respectively. The hourly consumption from February 2012 was extrapolated, with factor 1.10, to match the same total consumption as from 2015 for comparison reasons. Results obtained show that there was a shift from a relatively constant consumption throughout the day in 2012 to a distributed consumption in 2015 with a higher concentration in the off-peak time.

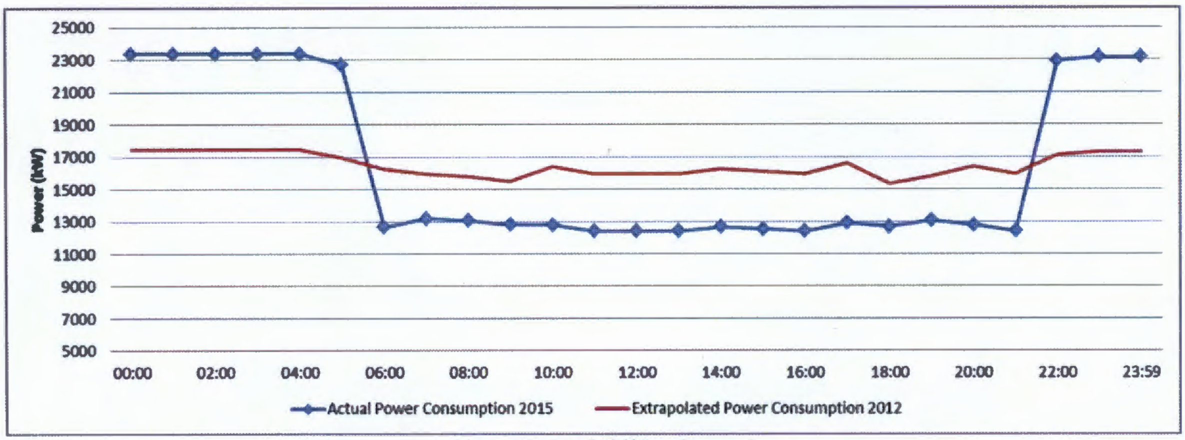

Figure 27: Load Shifting Comparison

The results are shown in the table below, where it can be determined that the foundry now uses 46% more electricity during off peak times, but 26% less during standard and 21% less during peak hours respectively. Given 2015/16 electricity prices, the load shifting saves the foundry about 526,742 ZAR monthly in low season. If same results were obtained in high season, the financial saving would be significantly higher at about 1,725,000 ZAR per month. Therefore it can be concluded, and agreed with found results in the literature review, that load shifting in South Africa as well as in a foundry, is a cost-effective solution.

	off peak	**standard**	**peak**	**Total**
February 2012				
Extrapolated Consumption (kWh)	4,440,637	5,795,235	2,535,157	12,771,029
Cost (ZAR)	1,730,072	3,355,441	2,150,066	7,235,580
May 2015				
Actual Consumption (kWh)	6,474,477	4,287,342	2,009,210	12,771,029
Cost (ZAR)	2,522,456	2,482,371	1,704,011	6,708,838
Saving (ZAR)				526,742

Table 7: Load Shifting Results

4.4.4. Summary

From the evaluation results obtained it can be seen that the implemented maximum demand management and load shifting saved the foundry a large amount of money without actually saving any energy.

The lighting project was one of the first energy efficiency projects the foundry implemented in 2011 and the second phase in 2012. Both projects turned out to be successful, jointly with the rebate from Eskom, payback periods were less than one year. Combined savings of 2,150 MWh resulted in improved energy efficiency and calculations show that about 37 kWh are reduced from the energy usage (kWh/ton produced).

However, as stated before, the foundry improved its actual usage by 90kWh since 2011, which points that further energy efficiency measures were also successful. The foundry has, for example, implemented ladle heating which allowed lowering the tapping temperature and hence reduced the specific power consumption of the induction furnaces. Furthermore, the maintenance team works continuously on fixing leaks of the compressed air system and compressed air wastage was reduced due to behavioural changes.

4.5. Further Proposed Energy Conservation Opportunities

Even though the foundry belongs to the top performers in South Africa, the rising electricity price threatens the competiveness, and calculations show that the energy cost will increase by 20% to 1,799 ZAR/t for the calendar year 2015. International competitors seem to have less issues with increasing electricity costs, ArcelorMittal SA, SA's largest steel producer, says in addition to earlier reviewed literature, rising energy costs are a threat to the competiveness of the South African market against the Chinese imports (Allix, 2015). Therefore energy efficiency improvements should be an ongoing process within the foundry.

Therefore the operation and energy conservation should further be improved; hence this section presents some possible further energy efficiency interventions identified for the foundry under review.

4.5.1. Compressed Air System

The foundry's maintenance team performs leak detection every three months. Nonetheless, the suspicion remains that the compressed air system uses more energy than actually required.
This chapter covers the findings from the compressor system analysis which was performed during one normal production-week in March 2015. Information is provided about the system and highlights opportunities for energy efficiency improvements.

The current compressed air system consists of three 530kW turbine compressors and two 275kW load screw compressors. While two of the three turbine compressors operate constantly, the third one is turned off and serves as emergency compressor. The two screw compressors are operating in on/off mode. The full load of all compressors accumulated is 2,140kW and the total compressed air delivery capacity combines to 21,300m^3/hour. Details of the compressors are shown in Table 8.

Compressor	Capacity Control	Power	Rated Capacity	Operating Pressure
1	Fixed Speed	530kW	90m³/min	3.1bar(g) – 10.3bar(g)
2	Fixed Speed	530kW	90m³/min	3.1bar(g) – 10.3bar(g)
3	Fixed Speed	530kW	90m³/min	3.1bar(g) – 10.3bar(g)
4	Load/Unload	275kW	42.5m³/min	5.1bar(g) – 9.2bar(g)
5	Load/Unload	275kW	42.5m³/min	5.1bar(g) – 9.2bar(g)

Table 8: Compressor System in Foundry under Review

The compressor assessment indicates that the compressed air usage accounts to 8,419,128kWh per year representing about 7% of the overall electricity usage.

Furthermore the assessment during a normal work-week showed an average compressed air delivery of 8,555m^3/hour with a pressure of 7.4bar. Hence the extrapolated compressed air supply annually is 74,570,496m^3, resulting in specific power consumption of 0.112kWh/m^3 and an average cost of 0.10 ZAR/m^3 for compressed air.

As literature suggests, compressed air is the most expensive form of power and a large amount of it is wasted due to leakages (Prashanth et. al, 2014). Therefore by the last leakage detection where joints, connections, valves and other common air leak areas are inspected, nine leaks of different sizes were identified. Estimations show that fixing the leaks results in a reduction of 403,000kWh per year and a cost saving of about 366,900 ZAR. The detailed calculation is described in Appendix I.

The compressed air system was monitored over a normal production week, including the weekend. According to the production manager there are only minimal production processes on Saturdays and no production processes on Sundays which require compressed air. Monitoring the compressor system showed that on Sunday the 15/03/2015 the lowest compressed air demand was required. Figure 29 illustrates the compressed air demand for this particular Sunday, highlighting the large combined average minimum demand rate of 3,012m^3/hour and a total delivered average of 6048m^3/hour.

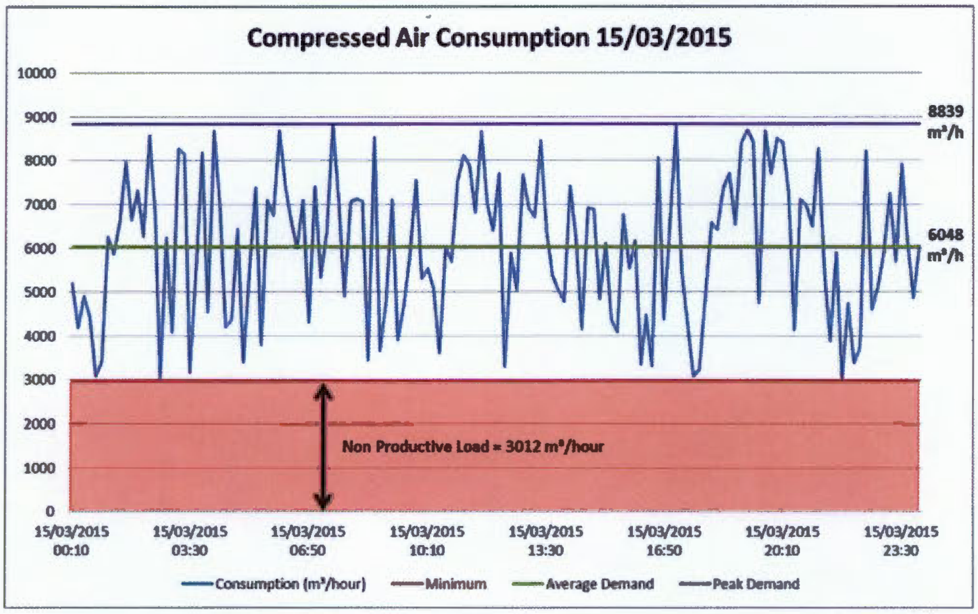

Figure 28: Leakage Rate Foundry Compressed Air
Based on monitoring results from 15th March 2015

The non-productive load is about 50% of the total delivered average 6048m^3/hour. It is assumed that most of the lost air is due to leakages, as there were no production processes during the measured time. This measured leakage rate amounts to 2,600,000 ZAR per year of electricity being wasted.

Although the maintenance team looks continuously for leaks the comprehensive test has shown that still a large amount of air is not used. Literature suggests that a leakage rate of 10 - 20% is considered acceptable (Kaya et. al, 2002; Saidur et al, 2010) and that an elimination of all air leaks is practically impossible, but given leakage rate of almost 50%, it should be addressed. A more accurate way to perform the leakage detection is the use of an ultrasonic leakage detector.

Furthermore, due to the fact that multiple compressors of different sizes are used, it should be assumed that they run at their most efficient load. Knowing the annual consumption from the monitoring system and Eq. 2.5.6.1 a load factor of only 59% was estimated. As literature suggests compressed air motors run the most efficiently at 75% or more of their rated load. A possible measure to improve the energy usage could be the adjustment of the motor speed with a VSD. According to literature this could achieve energy savings between 15-40% and furthermore extend the motors lifetime (Teitel et al, 2008).

4.5.1. Reduction of Holding Furnaces

The foundry under review operates three holding furnaces, as described in chapter 2.2.2. Molten metal is often held in a separate holding furnace before pouring it in the mould. This step allows continuous supply of molten metal and an uninterrupted pouring into the moulds. The disadvantage, however, is that this step consumes additional electricity. Naranjo (2005) claims, in terms of energy consumption, the ideal operation is pouring molten metal from furnace directly into the mould.

Energy Criteria

Currently the foundry operates a press pour furnace with 6-ton usable range and three holding furnaces, each with a power rating of 530kW and a measured consumption of 524 kWh/h. Given their 24 hours operation these holding furnaces consume annually about 4,600MWh resulting in a cost of about 4,200,000 ZAR.

Furthermore it will be evaluated whether the installation of a larger press pour furnace and therefore the elimination of the holding furnaces, could achieve a financial benefit. For evaluation and feasibility purposes a quotation from ABP Induction Systems GmbH was requested with an estimate price of 18-ton usable range press pour furnace, large enough to replace the three holding furnaces.

The pouring furnace is designed and used for holding, superheating and dispensing molten metals. Ideally the pouring furnace would be connected to the moulding lines, with delivery of the molten metal from the furnace into the pour siphon, as illustrated in Figure 30. The pouring process can be continuous also while the furnace is topped up.

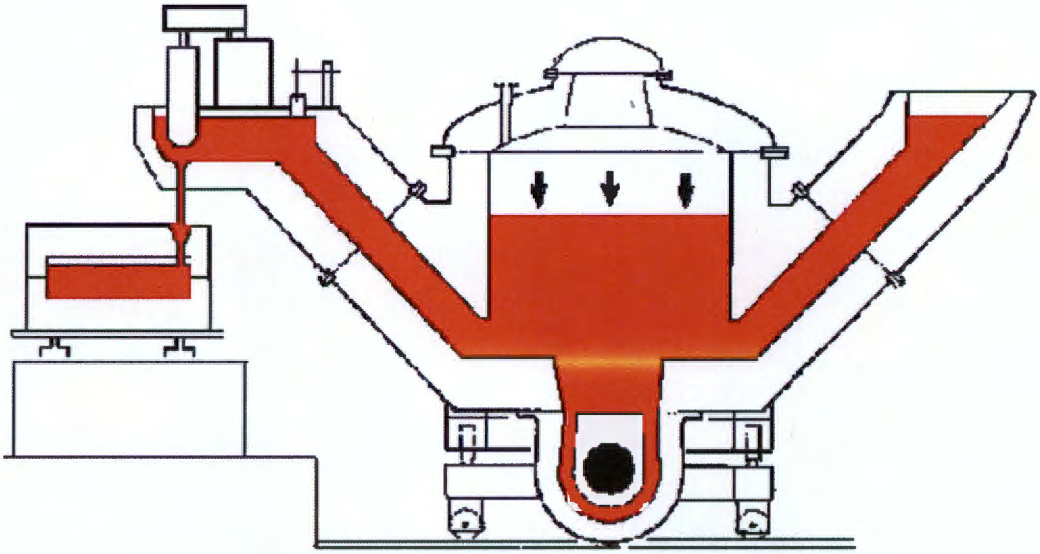

Figure 29: Schematic Drawing of Pressure Pour Furnace
(ABP Induction Systems, 2015)

Currently the three holding furnaces operate concurrently most of the time, as the production is on full utilization. Given their power capacity rating they are consuming about 13,800,000kWh a year which represents about 10% of the overall electricity consumption and a cost of 12,558,000 ZAR.

The provided budget proposal for a press pour furnace estimated an investment cost of 13,230,000 ZAR including installation.

Having a bigger press furnace will allow to shut down the holding furnaces; however, storing some molten metal in the holding furnaces is needed for the previously discussed load shifting. Therefore one holding furnace should be kept in operation and only two of the furnaces can be shut down, which in turn will result in an energy saving of 9,200,000kWh and about 8,400,000 ZAR. The power rating of the new larger press furnace is 500kW, which is equivalent to the smaller and much older press furnace; hence the power consumption can be neglected in this calculation.

The return of investment of the larger press furnace would be after 1.6 years and the continuous production flow is still guaranteed.

In conclusion it can be said that the installation of a larger press furnace would further reduce the foundries energy consumption without influencing the production output or the successfully implemented load shifting. Further due to reduction of electricity about 8,350 tCO_2 per year can be saved.

4.5.2. Preheating of Scrap Metal with LPG

Savings from preheating charge material are estimated to be between 5 – 10% (Albany Research Center, 2005) and studies have shown that preheating to an average of about 500°C will reduce the electrical requirements by 30 to 60 kWh/t and time throughput by 5 to 15% from EAF (Gandhewar, Bansod & Borade, 2011; Naranjo, Kwon & Majumdar, 2005). Most research and studies have been conducted on EAF; however, the UNIDO study examined the charge preheating for an induction furnace. Results showed savings of 25.4% if preheating the charge material to 450°C with a tapping temperature of 1500°C (UNIDO, 1998). The actual cost savings, however, are dependent on the tariff structure of the substitute fuel versus electricity rates (Prabhu, 2010). There have been no findings of preheating facilities for induction furnaces in South Africa.

Following a theoretical feasibility of preheating with LPG for the induction furnace at the foundry will be estimated to evaluate the effectiveness in a South African foundry.

Energy Criteria

The theoretical power consumption of the induction furnace with 1400°C melting temperature and 1450°C tapping temperature is according to Eq. 2.4.2 is:

$$Q_{th} = 312.7 \frac{\mathbf{kWh}}{\mathbf{t}}$$

While the energy requirement to tapping temperature from already 450°C preheated scrap metal would only be:

$$Q_{pre} = 219.2\frac{\mathbf{kWh}}{\mathbf{t}}$$

Therefore preheating the charge material will result in an energy saving of 93.5kWh/t which means 29.9% less energy will be required by the induction furnace. Comparing this value with the experimental results from literature shows that calculated savings are larger than suggestions by literature. However, the amount of 93.5kWh/t represents the theoretical saving and heat loss during transportation, conduction and radiation losses are not included. The key factor is the transport time between preheating station and the furnace, even a delay of a few minutes can result in a large heat loss due to radiation (Prabhu, 2010). Given Newton's Law of Cooling and assuming a transport time of one minute, the charge material would have temperature of 426°C when reaching the furnace. Hence a reduced saving of 88.40kWh/t is estimated.

$$Q_{th} - Q_{pre,t} = 88.4\,\frac{\mathbf{kWh}}{\mathbf{t}}$$

Given the power consumption rate and average electricity price of 2015, savings of 6,127,805 kWh and a cost saving of 5,576,000 ZAR are possible.

However, given the calorific value of CV_{gas}= 49.6 MJ/kg, it will require 6. 87 kg of LPG with an approximate cost of 87.89 ZAR/t to preheat scrap metal to 450°C, resulting in a total gas cost of 6,091,661.58 ZAR, hence gas preheating is not cost-effective.

Economic Criteria

Given that preheating is dependent on the cost structure of gas and electricity and knowing that the previously mentioned multiyear electricity price determination results in an electricity price increase of 12.69% annually until 2018 as well as the gas price, according to the International Monetary Fund, means it will not increase more than 0.5% over the next five years (IMF, 2015), gas preheating could be cost-effective in a later stage (Creamer, 2015b).

To model the economic feasibility of gas charge preheating in the long run, the cash-flow was modelled and illustrated in Figure 31. For calculation purposes, a conservative increase of 3% of LPG price annually was used.

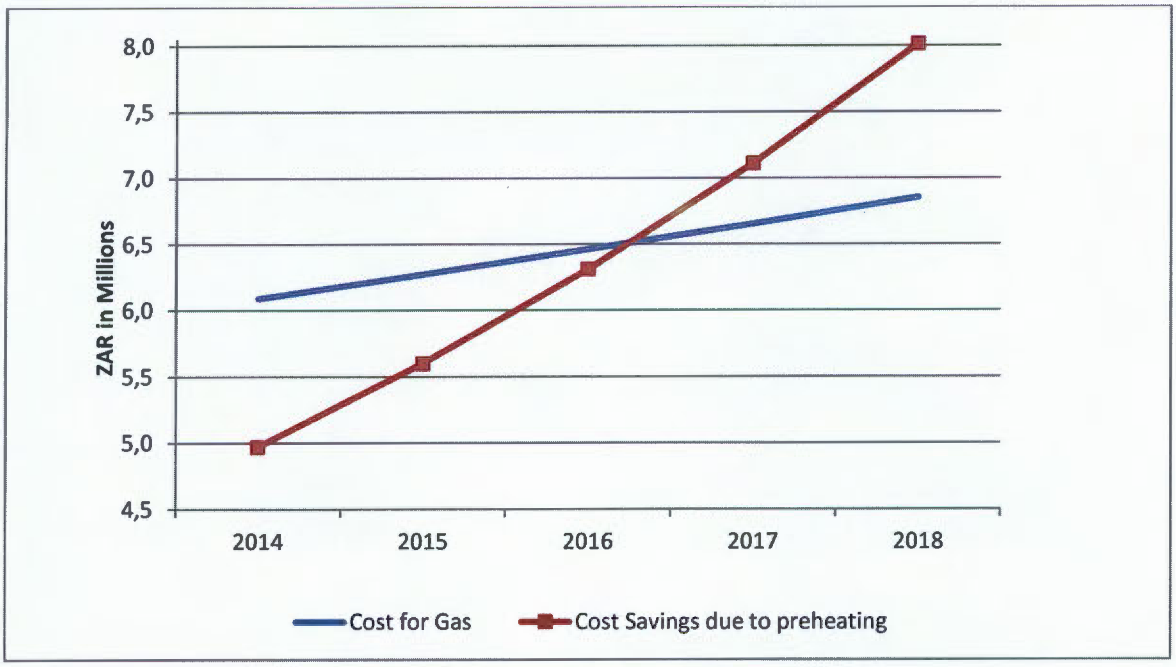

Figure 30: Preheating Cost Effectiveness Model with Increasing Prices

From the above figure it can be determined that from year 2017 gas preheating is a cost effective solution. Nonetheless a sensitivity analysis with increasing gas price and electricity price was performed as shown in Table 9.

	Current Values	Gas Price Inflation Scenarios			Electricity Price Inflation Scenarios	
Changing Factors:						
gas price	3%	1%	2%	5%	3%	3%
electricity price	12.69%	12.69%	12.69%	12.69%	18.0%	25.3%
Cost Saving:						
2015	-12.03%	-9.31%	-10.40%	-14.21%	-12.03%	-12.03%
2016	-2.40%	2.51%	0.56%	-6.41%	2.21%	7.91%
2017	6.41%	13.06%	10.44%	0.85%	14.64%	24.30%
2018	14.45%	22.46%	19.33%	7.61%	25.49%	37.77%

Table 9: Sensitivity Analysis - Cost Inflation Charge Preheating

As above Table 9 shows, even with a pessimistic gas price increase of 5% the gas preheating system is profitable from year 2017. Furthermore, if the electricity price increases as requested by Eskom, preheating the charge material would result in even higher savings, as the tariff ratio widens.

It can be concluded that preheating the charge material will result in a cost saving for the foundry from year 2017. Considering the economic criteria, it has to be noted that the initial cost of an additional preheating facility has not been taken into account. It is, however, assumed that no additional equipment other than gas burner in the charging shaft will be needed; hence the investment cost will be relatively low.

Environmental Criteria

The preheating system reduces the electricity consumption of the foundry substantially which in turn results in a carbon emission reduction of 5,570 tCO_2 per year. However, as the preheating system is a fuel switching technology, emissions are transferred to subsidizing fuel. In this case, burning LPG to preheat the charge material will emit about 2,930 tCO_2 per year. Given the lower emission factor of LPG ($EF_G = 0.447$ tCO_2/MWh) compared to the emission factor of South Africa's generated electricity ($EF_E = 0.909$ tCO_2/MWh), there would be a total net carbon emission reduction of 2,640 tCO_2 per year.

4.6. Summary of Evaluated Energy Efficiency Measures

The table below shows a summary of all evaluation criteria of the already installed and proposed energy efficiency measures.

Implemented and Evaluated Measures				
	Lighting	**MD Management**	**Load Shifting**	**Total per year**
Demand Savings (kVA)	268	1 900	-	**2 168**
Electricity Saving (kWh/year)	2 147 975	-	-	**2 147 975**
Cost Saving in 2015 (ZAR)	1 963 166	177 270	9 920 983	**12 061 419**
Emission Reduction (tCO_2/year)	1 953	-	-	**1 953**

Recommended for 2015				
	Compressed Air	**Reduction of HF**		**Total per year**
Demand Savings (kVA)	-	1 049		**1 049**
Electricity Saving (kWh/year)	2 955 133	9 188 014		**12 143 147**
Cost Saving in 2015 (ZAR)	2 638 512	8 397 487		**11 035 999**
Emission Reduction (tCO_2/year)	2 686	8 352		**11 038**

Recommended for 2017				
	Charge Preheating			**Total per year**
Demand Savings (kVA)	-			**-**
Electricity Saving (kWh/year)	6 127 805			**6 127 805**
Cost Saving in 2017 (ZAR)	455 668			**455 668**
Emission Reduction (tCO_2/year)	2 639			**2 639**

Table 10: Summary Case Study Findings

5. Conclusion

The aim of this thesis was to identify energy efficiency improvements for the South African foundry industry, which are both cost-effective and environmental beneficial. It was found that there is a lack of literature addressing the energy efficiency topic of South Africa's foundry industry. Some research identified the industry's energy intensity to be the highest in comparison with other BRICS countries. Given rising electricity prices and power constraints it was predicted that it is imperative to invest in energy efficiency measures to remain competitive.

Hence a case study approach of a large South African foundry was chosen to analyse energy intensity and energy efficiency measures. The method and case study was approached based on an industrial energy audit. It was identified that this method was useful to estimate energy usage as well as identifying where the use of energy can be optimized. The energy consumption and energy intensity of the foundry were analysed, based on meter readings, electricity bills and where necessary a "bottom-up" approach for estimation was used. Having established the current electricity usage, various energy saving strategies and technologies were evaluated and reviewed. For comparison purposes three distinct criteria were developed, namely energy, economic and environmental criteria on which all interventions were evaluated.

Reviewing the foundry it was found that about 127,000 MWh annually are consumed with a maximum demand of 26,500 kVA. The company under review has already implemented a number of energy saving measures since 2011, resulting in a decrease of their electricity usage of 5%. The identified energy intensity of 1,493ZAR/ton compares well to the South African average of 1,850ZAR/kWh. Further the specific energy consumption of the induction furnaces of 612kWh/ton lies within the better specified range from literature.

The energy consumption was reduced by about 2GWh per year, due to the successful implemented lighting projects which had both payback periods less than a year.

The maximum demand control as well as the load shifting were also evaluated and found to be successful in terms of cost saving. In total, it was estimated that load shifting saved the foundry 9,000,000 ZAR and the maximum demand control 1,900,000 ZAR in 2014. Furthermore, shifting the load from peak hours assists the national grid constraints and it can positively reported that the peak hour demand was reduced by 46%.

Further proposed energy efficiency measures included the compressed air system, preheating of the charge material and the reduction of the holding furnaces.
It was assumed that the compressed air system wastes a large amount of air due to leakages; hence the system was continuously monitored over a week with CS Air Systems Pty Ltd measuring equipment. It was found that about 50% of produced compressed air is unused due to leakage which accumulates to 2,955,000kWh being wasted. Assuming that all leaks could be fixed the foundry would save 2,600,000 ZAR in 2015 and could reduce the greenhouse gas emissions by 2,680tCO_2 per year. It was recommended that a leak detection with an ultrasonic sound detector rather than just a visual leak search be performed to identify more leaks. Nonetheless it is assumed, as stated by the literature, that eliminating all leaks is practically impossible.

As the foundry currently operates three holding furnaces, to provide continuous flow of molten metal to the press pouring, whether the operation could be reduced and perhaps replaced by a more efficient and larger press pour furnace, was investigated Given the successful load shifting, the assumption was made that one holding furnace should be kept in operation, while a new larger press pour furnace would offer further capacity to shut down two holding furnaces. It was found that reducing the furnaces and operating a larger press pour furnace will save the foundry 9,188,000kWh and about 8,400,000 ZAR in 2015 with a payback of 1.6 years. Furthermore, the carbon emission would be reduced by over 8,000 tonnes per year. Given the evaluation criteria, this intervention shows positive results and also does not hamper the continuous operation and production processes.

In order to improve the melting efficiency of the induction furnaces, preheating of the charge material was investigated in terms of theoretical calculations. It was found that preheating the scrap metal to 450°C about 28% of electrical energy could be saved during the melting process in the induction furnace. However, to preheat the charge material to the required temperature, about 6.8kg of natural gas are required. As confirmed by literature, the effectiveness of preheating with gas is dependent on the cost structure of gas and electricity, so it was found that given 2015 average electricity price of 0.91ZAR/kWh and a gas price of 12.8ZAR/kg preheating was not cost-effective.

Nonetheless the future cost structure was modelled to determine possible future cost-effectiveness. The model showed that gas preheating, given gas price escalation of 3% and electricity 12.69%, is cost-effective in year 2017 with saving the foundry 450,000 ZAR and following year 2018 1,150,000 ZAR. Moreover a sensitivity analysis was performed to test different gas and electricity price scenarios and it was found, that even with a pessimistic gas price escalation preheating shows positive results. It was concluded that gas preheating of the scrap material can represent a viable energy efficiency measure resulting in cost savings as well as net carbon emission reductions of about 2,600tCO_2 per year.

If all proposed energy efficiency measures are implemented, the effect of rising electricity prices will only have a marginal effect on the production cost and energy intensity of the foundry under study. The case study shows an overall positive result and scope for possible energy efficiency measures to undertake in the foundry under review. It can be concluded that energy efficiency is given energy, economic and environmental criteria viable in a South African foundry context. However, no general conclusion can be drawn as the case study approach limits the global reach. This means that other foundries in South Africa will not necessarily be able to achieve the same results; on the other hand, there might be foundries which have not implemented demand control or lighting interventions yet. From above evaluation it can be recommended to investigate in these measures to lower energy costs and reduce the strain on the national electricity supply.

As the recommended measures, especially the preheating of the scrap metal with gas, are theoretical calculations, it is suggested to research this topic further and perhaps perform experiments. Given the strongly increasing electricity price the ratio of the gas and electricity price is widening, hence gas preheating can be cost effective.

To summarize, it can be concluded that the overall aim of identifying energy efficiency improvements for the South African foundry industry, which are both cost-effective and environmentally beneficial, was successfully achieved. All evaluated measures, namely lighting, load-shifting and maximum demand management were a cost effective solution, and the carbon footprint of the foundry under review would be reduced. Furthermore the recommended energy efficiency measures, namely reduction of compressed air leaks, reduction of holding furnaces as well as preheating of charge material, showed in theoretical calculations a reduction of carbon emissions as well as cost savings. For a general conclusion of a South African context, further research could use a different methodology and assess a larger number of foundries.

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Appendix

A. Analysis Data Input Summary

a) Electricity and Production Summary

2014	Electricity Consumption (kWh)	Maximum Demand (kVA)	Cost (ZAR)	Production (ton)	Consumption Rate (kWh/ton)	Energy Intensity (ZAR/ton)
Jan-14	7,716,000	23,520	5,520,546	3715	2,077	1,486
Feb-14	10,402,400	25,653	6,728,174	5776	1,801	1,165
Mar-14	11,682,800	26,465	7,280,683	6266	1,864	1,162
Apr-14	10,733,700	26,507	6,958,174	5190	2,068	1,341
May-14	11,897,200	26,088	7,361,511	7491	1,588	983
Jun-14	12,252,840	26,466	12,299,061	6711	1,826	1,833
Jul-14	13,195,500	26,501	13,593,256	6680	1,975	2,035
Aug-14	12,338,940	26,481	12,569,664	7615	1,620	1,651
Sep-14	11,577,600	26,474	7,896,939	6143	1,885	1,285
Oct-14	12,482,931	26,459	11,121,364	6542	1,908	1,700
Nov-14	7,764,212	26,474	6,917,335	4277	1,816	1,617
Dec-14	5,054,800	26,459	4,835,617	2907	1,739	1,663
Total	**127,098,923**	**26,507**	**103,082,325**	**69313**	**Ø1,853**	**Ø1,493**

Sources:

Electricity Bills

Production Recordings

b) Melting Specific Data

		Unit
Melting Temperature	1,400.00	°C
Tapping Temperature	1,450.00	°C
Average Elec Price 2014	0.81	ZAR/kWh
Average Elec Price 2015 (estimation)	0.91	ZAR/kWh
LPG Price (estimation)	12.80	kg
Energy Intensity 2014	1,493.41	ZAR/ton
Energy Usage 2014	1,852.56	kWh/ton
Production Total 2014	69,312.86	tonnes
Electricity Consumption Total 2014	127,098,922.90	kWh/ton

Sources:

Information from Production Manager

c) Emission Factor

Emission Factor Electricity	0.000909	CO_2t/kWh
Emission Factor Gas	0.000447	CO_2t/kWh

Source:

Emission Factor Electricity: (Spalding-Fecher, 2011)

Emission Factor Gas: (Letete, Guma & Marquard, 2009).

B. Motor Count

Count	Power Rating (kW)	Annual Running Hours	Total Consumption (kWh)
1	200	8400	1680000
5	132	8400	5544000
2	158	8400	2654400
1	160	8400	1344000
1	220	8400	1848000
1	264	8400	2217600
			15,288,000

C. Compressed Air Leakage Calculations

Table Leakage rates (m^3/min) for different supply pressures and approximately equivalent orifice sizes

Pressure (bar)	Orifice Diameter (cm)					
	0.04	**0.08**	**0.16**	**0.31**	**0.62**	**0.95**
4.9	0.5097033	2.0388132	8.1552528	32.6210112	130.314144	293.928903
5.6	0.56067363	2.2087143	9.1746594	36.3588354	145.605243	327.909123
6.3	0.62863407	2.5485165	10.0241649	40.4364618	161.066243	361.889343
7.5	0.69659451	2.7184176	11.0435715	44.174286	176.697144	397.568574
8.75	0.83251539	3.398022	13.4221869	53.6887476	214.075386	482.519124

Equivalent Orifice diameter (cm)	Pressure barg	Number of Leaks	Leakage Rate (m3/min)	Factor	Days per week in Operation	Hours per Day in Operation	kWh required per m3	kWh Saved in One Year
0.04	7.5	0	0.70	0.80	7	24	0.11	-
0.08	7.5	2	2.72	0.80	7	24	0.11	4,269.87
0.16	7.5	2	11.04	0.80	7	24	0.11	17,346.33
0.31	7.5	3	44.17	0.80	7	24	0.11	104,078.00
0.62	7.5	2	176.70	0.80	7	24	0.11	277,541.34
0.95	7.5	0	397.57	0.80	7	8	0.11	-
Totals		9	632.90					403,235.54

Energy Cost in ZAR/kWh:	0.91
Total Energy Saved per Year (kWh):	403,235.54
Total Cost Savings for	
One Year's Operation (rand):	366,944.34

Sources:

Provided by Foundry Staff

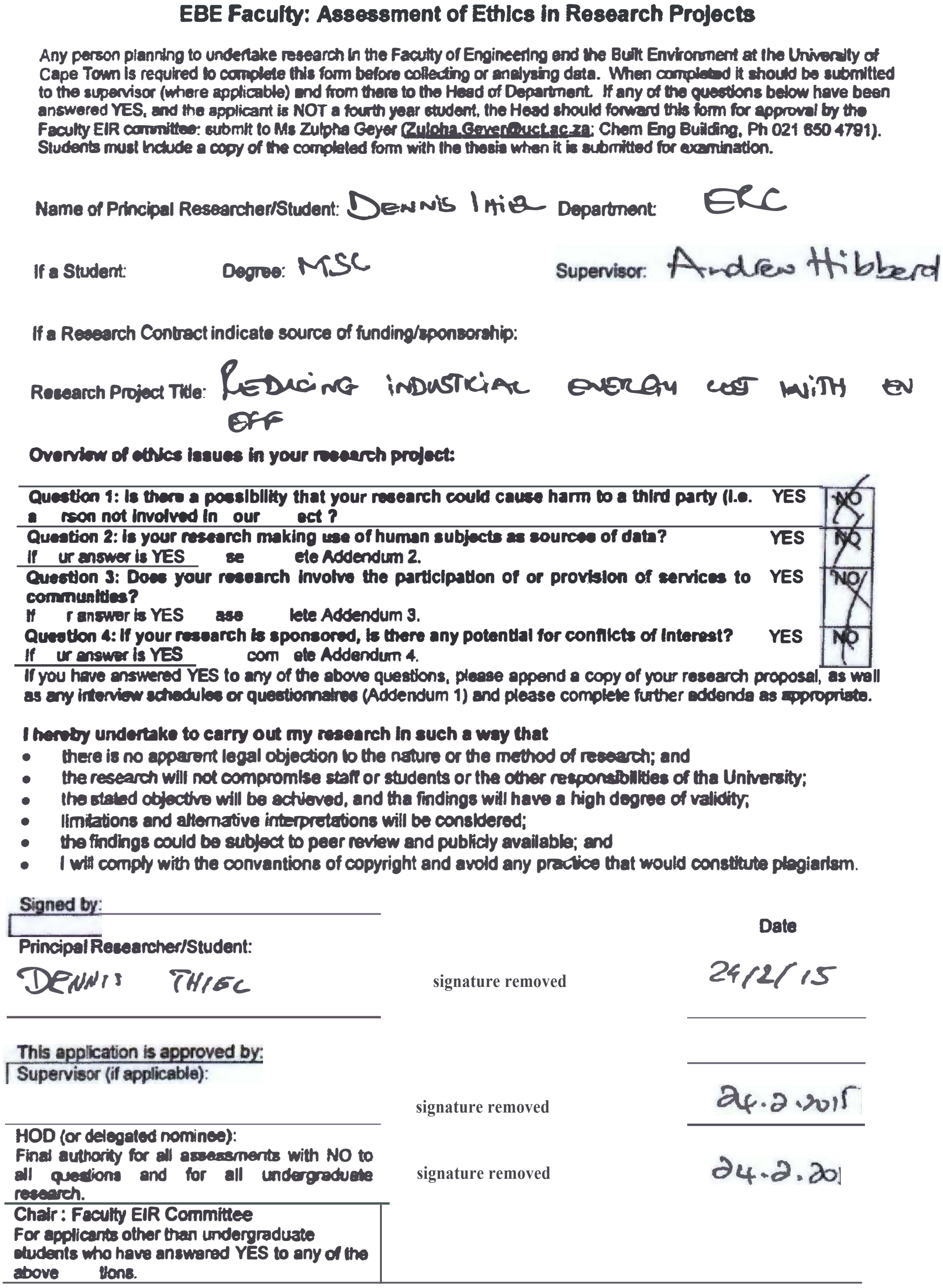
D. Lighting Calculations

Existing Technology	Qty	New Technology	Qty	LF	Unit Cost (ZAR)	Total Cost (ZAR)	kW before	kW saved	kWh before annual		proposed savings (ZAR)	incentive amount (ZAR)
400	531	100	479	1	3,250	1,556,750	212	165	1,860,624	419,604	1,441,020	792,561
400	135	50	135	1	2,500	337,500	54	47	236,520	29,565	206,955	113,825
						1,894,250	**266**	**212**	**2,097,144**	**449,169**	**1,647,975**	**906,386**

Monthly Demand Charge (R/kW) :	**R 81.00**
kW Demand Reduction :	**211.75**
Cost Savings from kW Reduction (year) :	**R 205,821.00**
kWh Energy Savings :	**1,647,975.00**
Cost Savings from kWh Energy Savings :	**R 840,467.25**
Eskom Incentive (0.55 R/kWh)	**R 906,386.25**
Estimated Annual Cost Savings :	**R 1,046,288.25**

Total Cost for Installation	R 1,894,250.00
Estimated Payback in Years (After Incentive)	0.97

E. Assessment of Ethics in Research Projects



EBE Faculty: Assessment of Ethics in Research Projects

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zulpha Geyer (Zulpha.Geyer@uct.ac.za; Chem Eng Building, Ph 021 650 4791). Students must include a copy of the completed form with the thesis when it is submitted for examination.

Name of Principal Researcher/Student: DENNIS THIEL Department: ERC

If a Student: Degree: MSC Supervisor: Andrew Hibberd

If a Research Contract indicate source of funding/sponsorship:

Research Project Title: REDUCING INDUSTRIAL ENERGY COST WITH EN EFF

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a rson not involved in our ect ?	YES	☒ NO
Question 2: Is your research making use of human subjects as sources of data? If ur answer is YES se ete Addendum 2.	YES	☒ NO
Question 3: Does your research involve the participation of or provision of services to communities? If r answer is YES ase lete Addendum 3.	YES	☒ NO
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If ur answer is YES com ete Addendum 4.	YES	☒ NO

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:		Date
Principal Researcher/Student: DENNIS THIEL	signature removed	24/2/15
This application is approved by: Supervisor (if applicable):	signature removed	24.2.2015
HOD (or delegated nominee): Final authority for all assessments with NO to all questions and for all undergraduate research.	signature removed	24.2.201
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above tions.		