OPPORTUNITIES FOR CONCENTRATED SOLAR THERMAL HEAT IN THE MINERALS PROCESSING INDUSTRY

S.A.C. Hockaday[1], **F. Dinter**[2] **and T.M. Harms**[3]

[1] Pyrometallurgical Division, Mintek; linah@mintek.co.za , MINTEK, 200 Malibongwe Drive, Randburg, South Africa

[2] Prof, Eskom Chair in CSP, Solar Thermal Energy Research Group (STERG); frankdinter@sun.ac.za

[3] Prof, Department of Mechanical and Mechatronic Engineering, University of Stellenbosch; tmh@sun.ac.za

Abstract

This paper aims to provide insight into possible applications of concentrated solar thermal heat in the ferro-alloy industry, specifically the upgrading of manganese ores by thermal decomposition and sintering, and the preheating of chromite ores before smelting. It evaluates each application with regards to capital and operating costs as well as environmental impact.

Currently the sintering of manganese ore fines is done in sinter plants where the combustion of coke in air provides the energy needed to achieve sintering and decomposition of carbonates in the ores. This scenario, called the carbothermic sinter, is compared to an alternative scenario (the solar sinter) where concentrated solar radiation is used to supply the needed energy.

Chromite ores are generally fed to ferrochrome smelters without pre-heating. An alternative scenario would be the preheating of chromite ores with concentrated solar radiation. Preheating of ores reduces the electricity requirements of smelters.

Financial evaluations of alternative process flowsheets looking at the payback period, the net present value of investments and the debt service coverage ratios in the proposed concentrated solar thermal process technologies are presented. The financial evaluation is used to determine which solar process has the best commercialisation potential.

Keywords: Solar thermal heat, minerals processing, sinter, preheating, concentrating solar, solar high temperature applications

1. Introduction

The treatment of manganese ores to produce sinter and the preheating of chromite ores for smelting have been identified as possible applications of concentrated solar thermal heat.

Manganese ores in South Africa are mostly exported with the exception of local ferroalloy smelters which consume a small part of the production. Other than sizing of the ore, the only beneficiation process that is practised by mines is the sintering of fines to produce an upgraded product suitable for charging to submerged arc furnaces. The sintering process is beneficial as it drives off any surface or chemically bound water, decomposes the carbonates in the ore, and achieves reduction of manganese minerals to Mn_2O_3.

Traditional sinter machines rely on the combustion of carbon to achieve the necessary temperatures for the thermal decomposition of $CaCO_3$ (850°C) and the softening of silicates in the ore (800°C) to achieve agglomeration and form sinter which meets the strength and size requirements of ferromanganese and silico-manganese smelters. The benefit of changing to solar heating from carbothermic heating would include less CO_2 emissions, reduced coke costs, and lower operating costs.

Ferrochrome smelters are energy intensive and preheating of the chromite ore with concentrated solar energy will reduce the amount of electricity required inside the furnace. In South Africa the grid electricity supply is predominantly from coal fired power plants, and lowering the amount of grid electricity required will therefore equate to CO_2 savings for the country.

The preheating of chromite needs to be coupled with the smelting process, and this will lead to additional complexity in smelter control.

These two possibilities were evaluated according to their energy requirements to size collector fields and then compared economically to identify the most promising research opportunity.

2. Energy requirements and sizing of the collector field

2.1. Energy requirements

The specific energy requirements (SERs) for each solar process were estimated for normalised compositions for manganese and chromite ores, seen in Table 1, using the equilibrium module in the FactSage 7.0 thermodynamic package [1]. The results are summarised in Figure 1.

wt %	Mn Ore	Mn Sinter	Chromite
MgO		9.2	10.9
$MgCO_3$	8.8		
Al_2O_3	0.5	0.6	14.4
SiO_2	4.0	4.5	4.0
CaO		16.4	0.6
$CaCO_3$	26.1		
TiO_2			0.6
V_2O_5			0.5
Cr_2O_3			43.9
MnO	29.6	12.0	0.2
Mn_2O_3		50.0	
MnO_2	23.2		
FeO			25.0
Fe_2O_3	6.6	7.3	
H_2O	1.3		
Total	100	100	100
Mn	38%	44%	N/A

Table 1. Compositions of materials as used for process evaluation

Although the mineralogy of the ores are more complex than these assumed compositions, the assumed compositions reflect the important reactions such as the evaporation of water, the thermal decomposition of $CaCO_3$ and also the reduction of MnO_2. The SER depends on the temperature required as well as on the energy requirement of any endothermic reactions taking place.

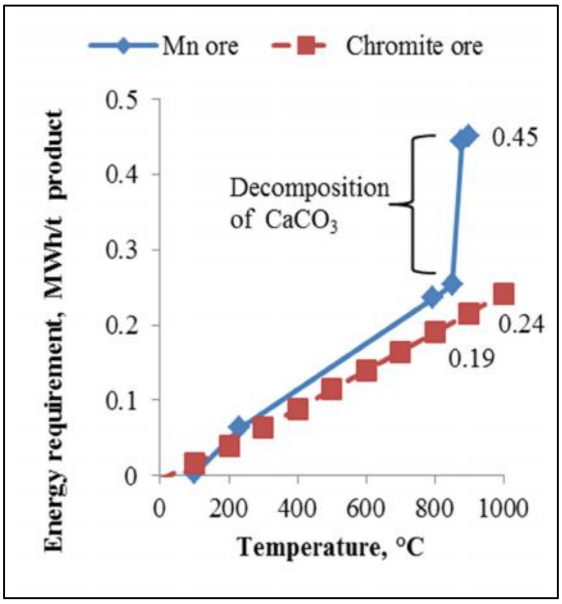

Figure 1. Energy requirements for sintering of manganese ore fines and preheating of chromite ore

The ferrochrome preheating scenario assumes pre-heating to 1000°C in order to size the heliostat field, but charges feed into the furnace at 800°C to account for heat losses during ore transfer.

The solar sinter scenario was benchmarked against data on manganese sintering from the paper by Pienaar [2]. The paper specifies coke as the carbon source but lacking analysis, we assumed petroleum coke with a fixed carbon content of 99.5 %. The energy transfer efficiency to the ore in the carbothermic sinter was calculated to be 61.6 % as 0.73 MWh/t sinter could be provided by complete combustion of the coke compared to the calculated requirement of 0.45 MWh/t sinter to reach 900 °C and complete $CaCO_3$ decomposition. This efficiency, $\eta_{reactor}$, has been assumed as to account for heat losses in the thermal processing unit based on sinter technology. This is based on the concept that the treatment units would be similar in construction and function to sinter plants. In Figure 2 the model concept is sketched and the efficiencies referring to the energy transfer steps are illustrated.

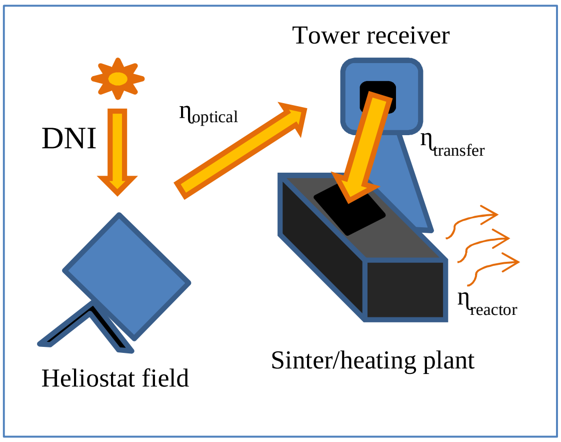

Figure 2. Sketch detailing model concept

Detailed experimental studies would be needed to determine $\eta_{transfer}$ as it is dependent on ore properties and the type of solar receiver used as well as the final design of the high temperature transport unit. This is outside of the scope of this paper, but will be the focus of future research. For the purpose of the economic models a value of $\eta_{transfer} = 0.8$ will be assumed.

2.2. Sizing of the collector field

In order to size the collector field several assumptions were made regarding the efficiencies of the energy transfer between the collectors and the receiver as well as the energy transfer between the receiver and the treatment plant. Given the energy requirements being more than 10 MW and the high temperatures required, a heliostat collector field with a beam down tower receiver is envisaged. If the beam down concept is impractical, different heat transfer fluids will be considered in future research.

The assumptions made for the model are given in Table 2. Lower direct normal irradiance (DNI) values are assumed for the chromite preheating scenario as most of the smelters are located near the Bushveld Minerals Complex in the North West Province and Mpumalanga, while the manganese mines are located in the Northern Cape Province.

DNI data were estimated from SolarGIS [3]. The heliostat field area was sized by relating the annual process energy requirement, $Q_{process}$, to the annual solar energy, Q_{solar}. These quantities are defined in equations 1 and 2.

$$Q_{process} = (SER) \text{ x annual production rate} \quad \textbf{1}$$

$$Q_{solar} = DNI \text{ x heliostat area} \quad \textbf{2}$$

$$Q_{solar} \text{ x } \eta_{optical} \text{ x } \eta_{transfer} \text{ x } \eta_{reactor} = Q_{process} \quad \textbf{3}$$

Parameter	Value
SER, Mn ore sinter , MWh/t	0.45
SER, Chromite preheating, MWh/t	0.24
Production rate, kt sinter/annum	500
$\eta_{optical}$, %	60
$\eta_{transfer}$, %	80
$\eta_{reactor}$, %	62
Collector area of total plant area, %	95
DNI, kWh/(m^2) Manganese sinter	2 700
DNI, kWh/(m^2) Chromite preheat	2 100

Table 2. Parameters used to size collector field

The optical efficiency of the heliostat field, $\eta_{optical}$, was assumed to be 0.6 and includes the cosine errors associated with tracking and reflecting solar rays to the receiver, mirror facet imperfections, scattering, blocking and shadowing and diffusion. This number has been reported [4] as high as 0.7 for electricity production facilities (receiver temperatures ≈600 °C) and as low as 0.6 for coal gasification applications (receiver temperatures ≈1000 °C).

The comparison of the sized fields for the solar manganese ore sinter and solar chromite preheater, as well as the solar plant thermal power ratings are given in Table 3.

Basis 500 kt product/a	Solar sinter	Chromite
Collector area, m^2	282 337	185 746
Plant rating, MW_{th}	60	39
Total plant area, ha	29.7	19.6

Table 3. Collector field sizes for solar projects

Due to the lower specific energy requirement, chromite preheating requires a smaller heliostat field even though the assumed DNI is assumed to be lower due to the location of the chromite smelters, see Table 3.

3. Economic evaluation

The high temperature treatment units required for both the sinter and preheating scenarios were assumed to be similar in operation to traditional carbothermic sinter equipment, with changes needed to accommodate solar radiation seen as negligible to costing. The major additional costs for solar treatment are the collector field and tower receiver.

Basis 500 kt product/year	**Carbo-thermic sinter**	**Solar sinter**	**Chromite preheating**
Availability, %	92.5	47.4	38.6
Production, t/h	68	134	164
Production, t/day	1 519	1 519	1 519
Carbon, kg/t sinter	105.9		
Total CO_2, kt/year	319	103	0

Table 4. Comparison of carbothermic sinter data (Pienaar, 1992) with solar sinter and chromite preheating scenarios

3.1. Capital costs

Numbers sourced in different currencies were converted to South African rands using the exchange rate at the year of estimation [5] and adjusted applying CPI inflation [6].

Capital costs, Million R	**Carbo-thermic Sinter**	**Solar Sinter**	**Solar Preheater**
Treatment	365	711	873
Heliostat field	-	689	453
Tower	-	135	88
Land	-	0.18	0.12
Total	365	1 535	1 414

Table 5. Capital cost estimation

Capital costs for each process are given in Table 5. The carbothermic sinter cost is based on the cost of the sinter installed for Kalagadi mine in 2012. The 2.4 Mt sinter/annum plant was bought for R 1.4 billion [7]. Sinter costs are assumed to be linear based on the hourly production rate. The hourly production rate was calculated for each process and is given in Table 4.

The cost of the treatment unit for the chromite preheating is assumed to be similar to the cost of a sinter unit as they share the same high temperature requirements and mechanics. The treatment unit costs for the solar processes are larger as they are required to handle a higher throughput than the conventional unit which has a much higher availability.

The capital costs for the solar sinter and the chromite preheater are similar, with the solar sinter requiring a larger heliostat field while the chromite preheater requires a larger treatment unit. The cost of the treatment unit is estimated to be larger than the cost of the heliostat field and the receiver tower.

The cost estimated for the tower receivers are based on estimates by Hinkley (2013) [8] for towers as 217 AUS$/kWth and the heliostat field costs are based on values from IRENA (2015) [9] at 147 USD/m^2.

Land costs were calculated based on an assumed land price of R 6 000/ha.

3.2 Operating costs and profits

The operating costs for the carbothermic smelter include the cost and transportation of coke. Coke transport costs were based on estimates by Ramsay [10] at R 1.11/ (t.km) and a 726 km distance from supplier to the manganese ore mine. Petroleum coke at R 4 600 /t was used to determine carbon costs. From the mass balance 53.2 kt of coke is needed to produce 500 kt sinter annually. Operating and maintenance costs were estimated using reports for the Kalagadi Mine sinter plant [11] adjusted according to annual production and from data published by IRENA [9].

The solar preheating of chromite has an annual saving on electricity costs. The annual amount of electricity saved was calculated as 95 GWh/a. An average electricity price of R 0.50 /kWh was assumed in 2016 based on data from ESKOM [12] and an annual electricity escalation of 10 % is included in the model.

Manganese ore and sinter are sold based on their manganese metal content. This price has been constant at around R 25 000/t manganese over the last 5 years [13], as South African exports control a large share of the market. The economic evaluation assumes that 15 % of the sales from manganese sinter can be considered profit with the remaining 85% being absorbed by mining, sizing and transport of the product.

The assumptions for each scenario considered are given in Table 6 and Table 7.

Variable	Assumption
O&M escalation	0%
Corporate Tax rate	28%
Depreciation period, years	10
Cost of debt (loan rate)	15%
Carbon Tax, R/tCO_2	0.00
Coke cost, R/t	4 620
Coke transport cost, R/t	806
Coke cost escalation	0%
Transport cost escalation	0%
Discount rate	15%
Electricity cost, R/kWh	0.50
Electricity cost escalation	10%

Table 6. General assumptions for financial models

	Carbo-thermic sinter	Solar sinter	Chromite preheating
Capital Costs, R million	365	1 535	1 414
Coke, t/year	53 200	0	0
O&M, R million/year	19	134	98
Loan period, years	10.00	15.00	10
Product, kt/year	500	500	500
CO_2, t/year	318 751	103 477	0
Profit on sinter	15%	15%	-
Mn in sinter	44%	44%	-
Mn price, R/t	25 000	25 000	-
Mn price escalation	0%	0%	-
Annual electricity saved, GWh			95.14

Table 7. Scenario specific assumptions for financial models

4. Results

The constructed economic models were used to evaluate the scenarios for a period of 15 years.

Payback and net present value (NPV) were calculated as described by Atrill [14] and mathematically expressed in equation 4.

$$NPV(r,n) = \sum_{0}^{n} \frac{C_n}{(1+r)^n} \quad (4)$$

Where C_n = Net cash flow in year n

r = discount rate

n = year

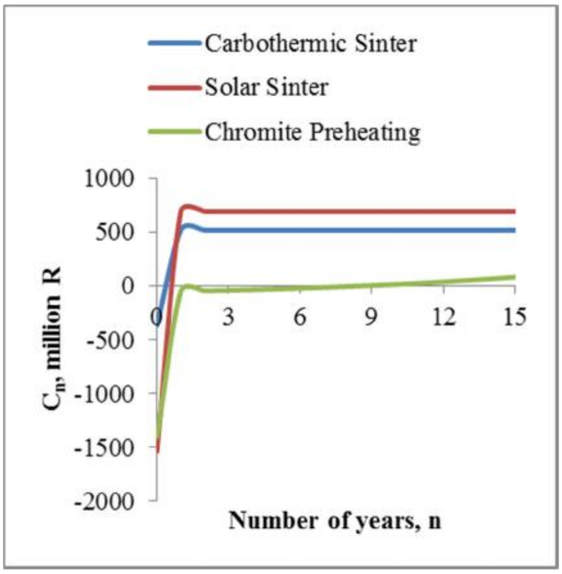

Figure 3. Net cash flow comparison

A cash flow comparison, see Figure 3, showed that the solar sintering of manganese ore is the more appealing research option as the sales of manganese sinter can off-set the high capital costs required, while the annual savings in electricity from preheating chromite smelter feed is insufficient to cover operations and maintenance costs until year 8.

NPV comparisons in Table 8 show that solar chromite preheating, based on the assumptions of this paper, does not achieve a positive NPV.

	Carbo-thermic sinter	Solar sinter	Chromite preheating
NPV, R million	2 670	2 514	-1 523
IRR, %	142%	45%	-13%
Years to payback	1	3	23

Table 8. NPV and IRR calculated for scenarios

The internal rate of return (IRR) defined as the discount rate leading to a NPV of zero, is also given in Table 8. Since there are large differences in capital costs, the NPV is seen as a truer reflection of the proposed project value than the IRR, and sensitivity analysis of the model will refer to the effect on the NPV.

In addition to the NPV, the debt service coverage ratio (DSCR) for the carbothermic and solar sinter projects were calculated to determine that enough cash flow exists to cover debt payments. In general a DSCR of 1.3 is assumed sufficient to reduce investor risk.

$$DSCR = \frac{PADT + D + IPMT}{PPMT + IPMT} \quad (5)$$

Where PADT = Profit after depreciation and tax
D = Depreciation
IPMT = Interest payment on debt
PPMT = Principal payment on debt

The values determined are shown in Figure 4. The carbothermic sinter scenario has very good debt coverage and the debt coverage of the solar sinter is sufficient over the total loan period. A longer loan period was however required compared to the carbothermic scenario.

In addition to the comparison between the solar processes it was also interesting to see the model comparisons between the carbothermic and solar sinter scenarios. The following sensitivity analysis illustrates how sensitive the model is to changes, and under which circumstances the NPV of the solar sinter would outperform that of the carbothermic sinter.

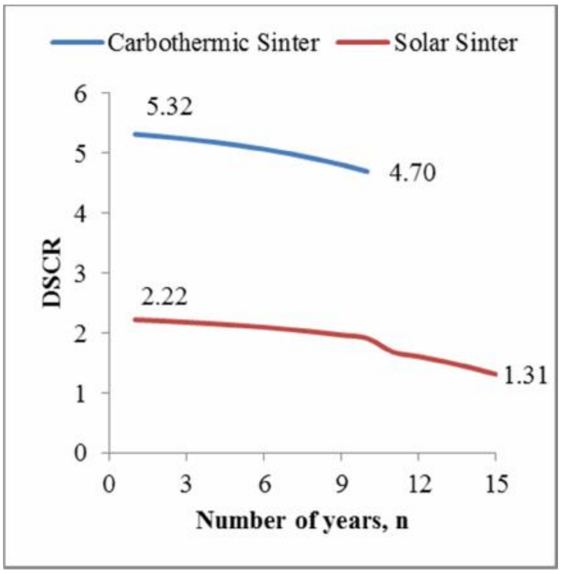

Figure 4. DSCR for sinter scenarios

4.1 Capital cost sensitivity analysis

The influence of capital cost is certainly one of the main parameters when evaluating project feasibility, and therefore the effect of a capital cost reduction (including the treatment unit) in all scenarios was evaluated.

The main conclusion stands, but the solar sinter option moves closer to the traditional carbothermic sinter as it becomes a more attractive investment. Capital costs are affected by the cost of physical equipment such as the heliostat field, receiver tower and high-temperature treatment/sinter unit. These are in turn determined by the process design values such as production rate, the solar resource and the efficiencies assumed in equations 1 and 2.

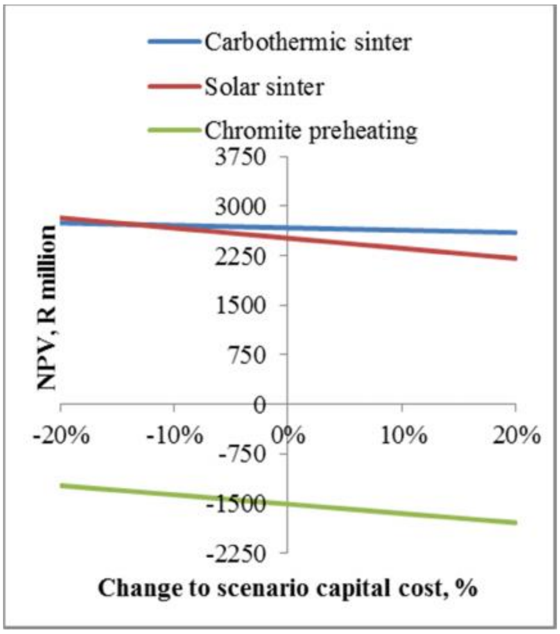

Figure 5. NPV sensitivity to changes in capital costs

4.2 Operating and maintenance costs

The effect of annual escalation of operating and maintenance costs (excluding coke and coke transport) on the NPVs is presented in Figure 6. The solar sinter scenario is most affected as it has the highest annual operating and maintenance costs.

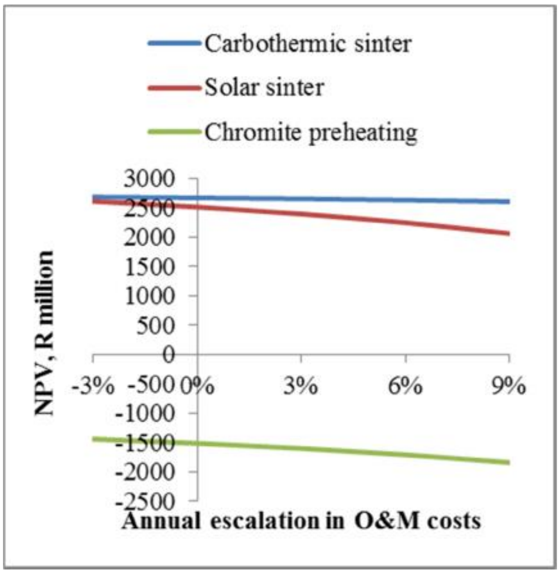

Figure 6. NPV sensitivity to escalation in O&M costs

4.2 Coke and transport costs increases

For the baseline scenario, coke and coke transport costs were considered static. Annual escalation in both these costs affects the carbothermic sinter negatively as shown in Figure 7. The South African road infrastructure has been under severe strain due to heavy commercial traffic [10] and the national rail infrastructure has limited capacity. The reliance on transport is a weakness of the carbothermic sinter scenario, but while transport costs remain low and the road network remains adequate, it will remain the most attractive option. If increased rail capacity comes online transport costs may even reduce, increasing the carbothermic smelter profitability. As the solar sinter does not use coke it is unaffected by variation of these costs.

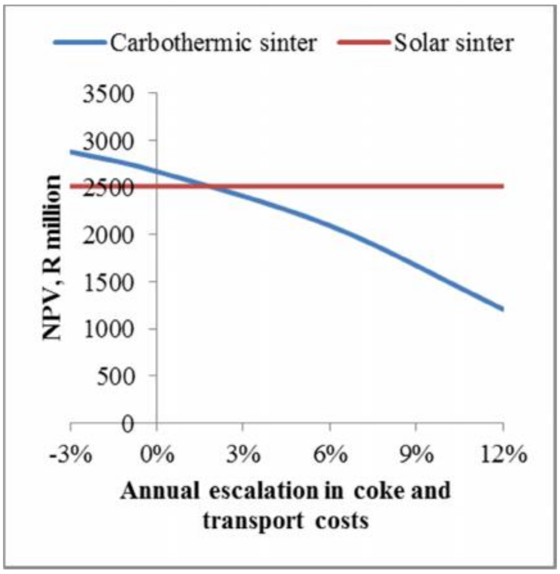

Figure 7. Effect of coke and transport cost escalation on scenario NPV

A 10 % static increase in the price of coke would lead to parity of the scenario NPV's as is shown in Figure 8, while transport costs would have to increase by 60 % to achieve the same effect (see Figure 9). We therefore conclude that the NPV of the carbothermic sinter is more sensitive to the coke price than to the cost of transport.

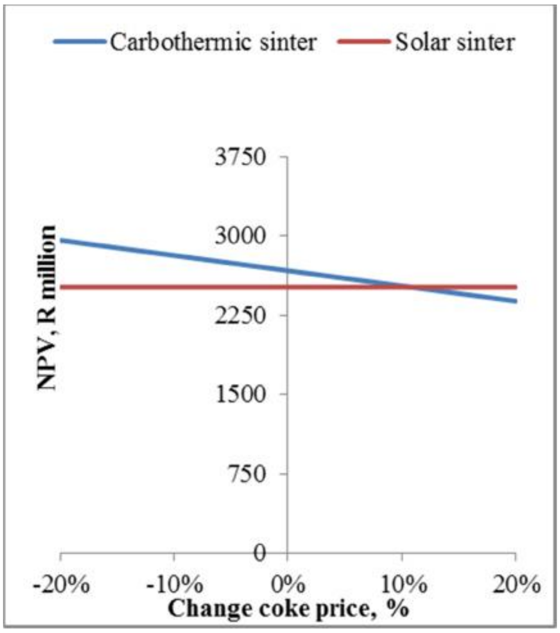

Figure 8. Sensitivity to coke price change

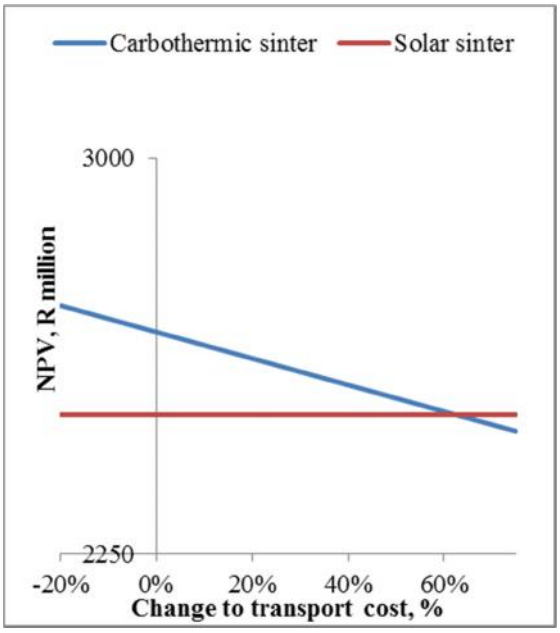

Figure 9. Sensitivity to transport cost change

4.3 Profit on sinter sales variance

Sinter processes are vulnerable to changes in the amount of profit on manganese sinter. Changing the amount of profit from 15 % to 7.5 % of sales makes the projects marginal and both the carbothermic and solar sinter process show negative NPV's at a 5% profit on sinter sales.

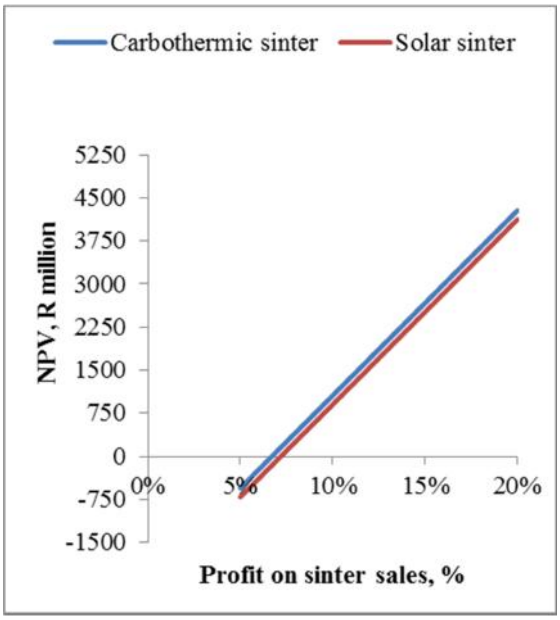

Figure 10. Sensitivity of NPV to changes in profit on sinter sales

4.4 Carbon tax insensitivity

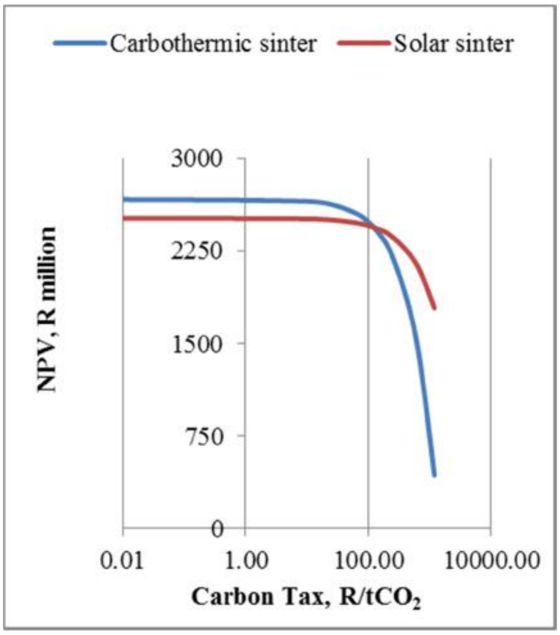

Figure 11. Influence of carbon tax on sinter economics.

From Figure 11 it can be seen that the proposed effective carbon tax of R 12 /t CO_2 [15] does not have large influence on the NPV of the carbothermic sinter. It may be concluded that the process economics are insensitive to carbon taxes up to the value of R 124 /t CO_2 where the NPV for the carbothermic and the solar sinter are equal. Any increase above R 124 /t CO_2 clearly advantages the solar sinter process.

5. Conclusion

In this paper, an evaluation of the application of concentrated solar thermal heat to two minerals processing scenarios through economic models has been presented. The preheating of chromite feed using a high-temperature heating unit based on sinter plant technology integrated with a receiver tower and a concentrating heliostat field only achieved payback after 23 years and never achieved a positive net present value when compared to a discount rate of 15 %. The sintering of manganese ore fines, based on similar assumptions, achieved payback within 2 years and a positive NPV and IRR. Research of the solar sintering of manganese ore fines would therefore be more likely to lead to commercialisation than research into the preheating of chromite smelter feed.

The solar preheating of chromite might become feasible if the scenario is redefined to include income from ferrochrome sales as well as electricity savings.

Evaluation of the traditional carbothermic sinter showed that it remains the scenario with the highest net present value as evaluated over 15 years, based on the assumptions made in this paper.

Capital cost of the solar heating scenarios as well as uncertainty in design assumptions remain the biggest barrier to implementation of concentrated solar thermal heat in the minerals processing industry, as operating costs including raw material costs, were estimated to be lower for the solar sinter and solar preheating scenarios than for the carbothermic sinter scenario. Further research is needed toward the reduction of capital costs required for the concentrated solar thermal heat plant, but also toward the efficiency of heat transfer from the solar receiver into the treated ore.

The cost of coke and coke transport in the model of the carbothermic sinter shows that a 3 % annual increase in these costs will make the NPV on par with that of the solar sinter process.

The economic models of both the carbothermic and solar sinter scenarios are sensitive to the amount of profit made on sinter sales, and the solar sinter would not show a positive net present value compared to a 15 % discount rate if the profit on sinter sales falls below 7.5 %.

The economic model derived in this paper showed that the proposed carbon tax does not influence the outcomes of the model if it remains below the value of R 124 /tCO_2.

Future studies are also recommended into hybrid systems where solar heating may be used to reduce CO_2 emissions, but supplemented with fossil fuels to maintain throughput while lowering the size (and cost) of the sinter plant, solar field and tower.

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