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A Sensitivity Analysis of the High-Temperature Solar Pretreatment of Calcite-Rich Manganese Ores

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Abstract. The modelling of high-temperature direct solar thermal treatment of manganese ores found that a heliostat field and tower process rated at 2.5 MW_{th} will treat roughly ten thousand tons of material annually, producing calcined products of consistent grade. This paper looks at a sensitivity analysis of the results when changing the solar irradiance and financial parameters. The sensitivity analysis shows that a 10% decrease in solar irradiance increases the levelised cost of heat by 5% while decreasing the production by 5%. The levelised cost of heat (LCOH) was most influenced by the cost of the heliostat field as the largest component of capital expenditure. Changes in the interest rate also have a significant impact on the levelised costs of the pretreatment.

Keywords: Solar Thermal Treatment, Manganese Ores

1. Introduction

The necessity of reducing greenhouse gas emissions to limit the impact of anthropogenic climate change means that all industrial processes should investigate their options towards decarbonisation. Iron, steelmaking, aluminium, and cement production produce the most industrial emissions. Although most research focuses on decarbonising these industries, other minerals processing industries must also be decarbonised to achieve net zero emissions by 2050 goals. Incorporating renewable energy sources and avoiding the combustion of fossil fuels are two ways to reduce greenhouse gas emissions. The direct solar thermal pretreatment incorporates both of these strategies.

The direct solar treatment of manganese ores has been performed on a small scale, 350 g to 500 g batches, and showed promising decomposition of carbonate minerals [1]. The upscaling of direct solar thermal treatment of manganese ores has been investigated based on several models describing the solar resource [2], the manganese ore reaction kinetics [3], and a solar particle reactor [4], as shown in Figure 1. These models were dynamically linked in HSC Sim [5], [6] to estimate the annual production and composition of solar thermal pretreated manganese ores [7]. The solar plant was designed with a maximum power rating of 2.5 MW, but the energy demand is 1.7 MW. This is equivalent to a solar multiple of 1.5. The location considered was Hotazel, South Africa, with an annual direct normal irradiance (DNI) of 2843 kWh and close proximity to several active manganese mines with projected life of mine of more than 40 years. Design of the heliostat field and modelling of the solar receiver are described in detail elsewhere [7], Chapters 9 & 10. The central receiver is modeled based on published data for the Centrec™ receiver [4], [8], [9] and it is assumed that the manganese ore is of a similar particle size as the sintered bauxite particles used in testing the Centrec™

receiver, around 1 mm diameter, and behaves in a similar fashion. Although care was taken to use a energy efficiency model of the receiver based validated against published results, it should be noted that further challenges may be expected that will be neglected in this paper. Assumptions of the ore behaviour as similar to bauxite particels and the ore losses to atmosphere will need to be confirmed in future research. Nevertherless, manganese mines have readily available fines, <6 mm diameter, that may be sized and screened to meet the requirements of the centrifugal receiver [10]. Challenges presented by the open centrifugal receiver are expected to be dust losses due to fines generation and possible dumping due to less spherical paricles having non-ideal flow behaviour.

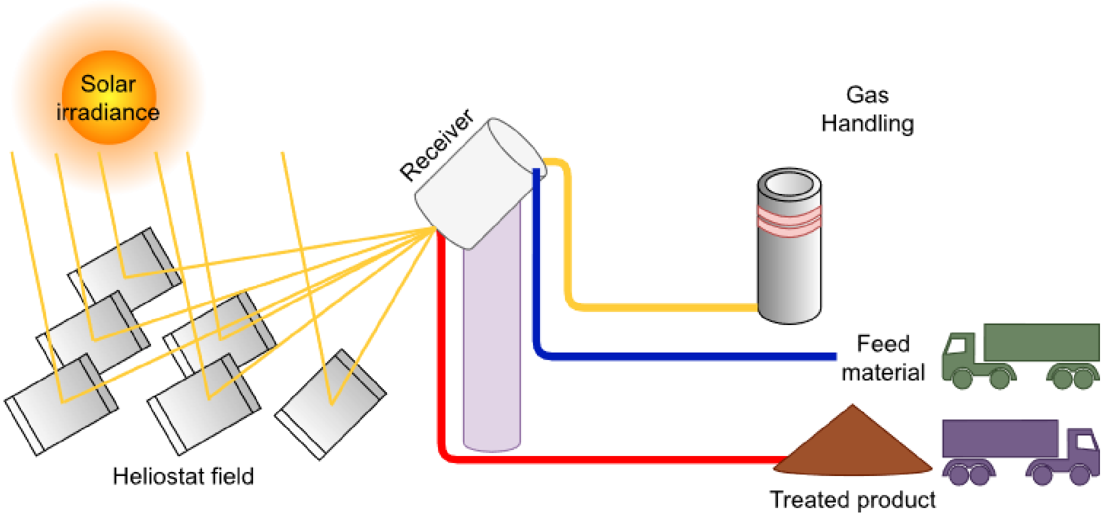

Figure 1. *CST plant process illustrating components for direct manganese ore heating concept [7].*

The smelting of the manganese ores to produce ferromanganese is not co-located with the pretreatment process. It is therefore not necessary to incorporate thermal storage and materials can be stockpiled before transport via road or rail and/or shipping to smelters around the world [11], [12].

The energy demand of solar-treated material in a high-carbon ferromanganese furnace was then investigated based on an HSC Sim equillibrium distribution model, as shown in Figure 2. Manganese ores are fed to the smelters with silica as flux and coal as reductant. The reductant requirement was determined by the amount of oxygen removed from the ore to reduce the iron and manganese to the metal and the carbon reporting to the alloy. The electricity demand was based on the sensible and latent energy required to heat all the materials to the smelting temperature and the net energy demand from all the reactions. The specific energy requirement (SER) to produce a high-the carbon ferromanganese alloy (78 % Mn, 7.5 %C remainder Fe) at 1300 °C, slag at 1500 °C and off-gas at 700 °C, was estimated based on an HSC distribution model with carbon addition of twice the stoichiometric requirement. Silica flux was added to maintain the furnace basicity around 1.28 [13].

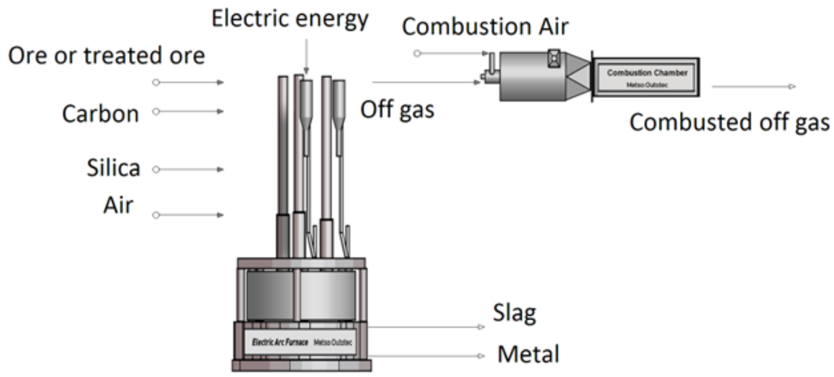

Figure 2. *Schematic of high-carbon ferromanganese smelter model*

It was found that manganese ores with a high amount of calcium carbonate and other carbonate minerals undergo significant calcination and limited thermal decomposition of manganese oxides during thermal pretreatment, leading to a product that requires up to 50 % less electricity for smelting compared to untreated ores [7] Chapter 10.4. Some ores will even have lower electricity demand for smelting than manganese ore sinter [3], while having with a reduced carbon footprint due to replacement of coke breeze and diesel in sinter production with solar energy. CO_2 process emissions is the same for solar thermal pretreatment as for sinter production and are not addressed in the scope of this work.

The total CAPEX of the solar treatment plant was estimated as 669 kUS$. Cost assumptions as given in Table 1 with source references. Source values were adjusted for annual inflation in South Africa and conversted to US$.

Table 1. *Cost assumptions for LCOH calculations*

Item	Value
Heliostat field cost [14]	3760 ^{m2} @ 106 US$/m^2
Tower cost [15]	42 557 US$
Receiver cost [15]	112 398 US$
Vertical particle transport [15]	114 646 US$
Land cost [16]	179 US$/ha
Indirect costs	22% of CAPEX
Annual insurance costs	1% of CAPEX

The LCOH was calculated for different payback periods and compared to grid electricity costs in South Africa [17] in Figure 3 according to accepted methodology [18] assuming an interest rate of 7 % and a discount rate of 10 %. As the manganese resources in South Africa is sufficient for another 40 years of production at current mining rates, if a project lifetime of 30 years is assumed, at least 10 years of operation after capital repayment is feasible.

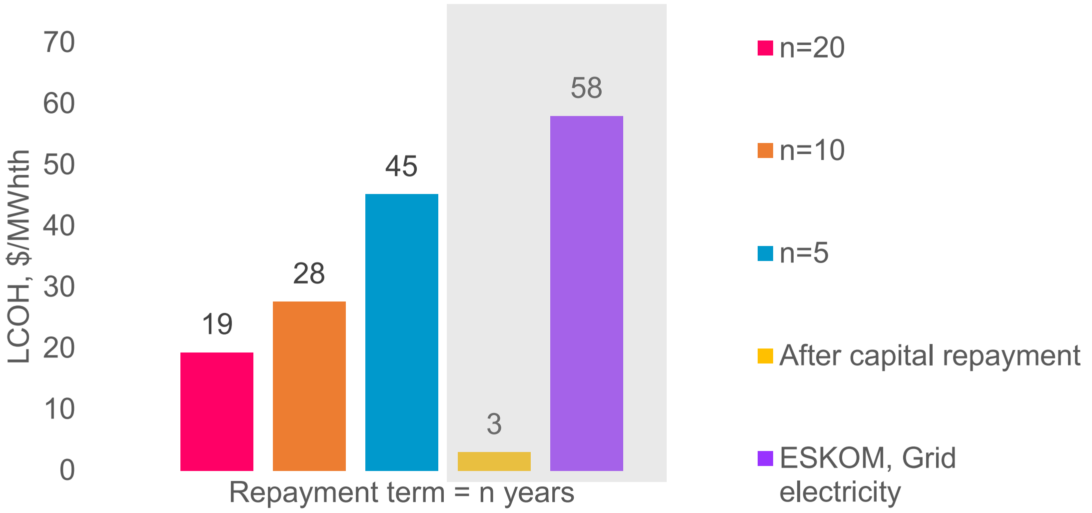

Figure 3. *LCOH calculated for different payment periods compared to grid electricity costs in South Africa and annual operating and maintenance costs after loan repayment*

The levelised cost of electricity for solar PV has been estimated as 50 UD$/MWh in 2022 [19] and the solar thermal treatment is therefor also cost competitive with thermal treatment by an electrified kiln heated with electricity from standalone solar PV. This comparison superficial but promising as considerations such as land requirements and electric heater cost for solar PV heating is outside the scope of the current paper.

This paper reports a sensitivity analysis of results from a dynamic process model developed to investigate the feasibility of concentrating solar thermal pretreatment of manganese ores for increased ferromanganese smelter productivity and reduced greenhouse gas emissions [7].

2. Methodology

The sensitivity analysis was conducted by comparing the results from simulations with a modified input to the base case reported previously. For the base case, the ore composition may be described as in Table 2. The reaction kinetics for this material in air is described in detail previously [3]. The time period for the simulations was the tmy month of March. The dynamic simulation uses hourly DNI data as input, but the simulation timestep is 1 minute as the required residence time in the solar reactor is around 6 minutes. Future studies could run simulations with DNI input for each minute as well as this will give an even better evaluation of the system productivity, but this is outside the scope of current work [7] Chapters 9 & 10.

Table 2. *Ore composition for current study*

Mineralogy	wt %
MnO_2	2.56
Mn_7SiO_{12}	41.74
Mn_2O_3	0.84
Mn_3O_4	7.19
SiO_2	3.42
Fe_2O_3	6.18
K_2O	0.05
Cr_2O_3	0.51
P_2O_5	0.06
$BaSO_4$	0.37
Na_2O	0.03
C	1.78
$CaMg(CO_3)_2$	17.61
$CaCO_3$	16.48
$Mn_2O_3.3H_2O$	0.09
$Al_2O_3.3H_2O$	1.09
Total	100

Firstly, changes in the annual solar irradiance were investigated by multiplying the solar irradiance (in the tmy weather file) by factors of 0.9, 0.95, 1.05 and 1.1. The modified weather files were then used as input to the process model and simulations were run to see the effect of the changes in input. The simulation was run for the month of March in the tmy which shows significant weather effects as it is the wet season at the proposed plant location. The changes in throughput of material, used thermal energy and levelised cost of heat (LCOH) are then reported as results.

Secondly, for the base case solar irradiance, parameters in the financial costing model were investigated and the resulting LCOH calculated.

3. Results and discussion

Since the thermal plant was designed with a solar multiple of 1.5, sufficient flux for treatment was available for 6 to 8 hours on sunny days.

The operating strategy fed material to the receiver while the temperature at the receiver discharge remained above 970 °C. Feed rates were at 1600 kg/hr when the solar flux to the receiver was below 1000 kW/m^2 and 3200 kg/h when the solar flux was above 1000 kW/m^2. The solar flux to the receiver was limited to 1700 kW/m^2 by de-focussing heliostats to prevent the product temperatures from reaching 1200 °C and sinter formation.

3.1 Analysis of sensitivity of operation to solar irradiance

The sensitivity of the thermal energy used in the process, material throughput, and product quality to changes in DNI is given in Figure 4.

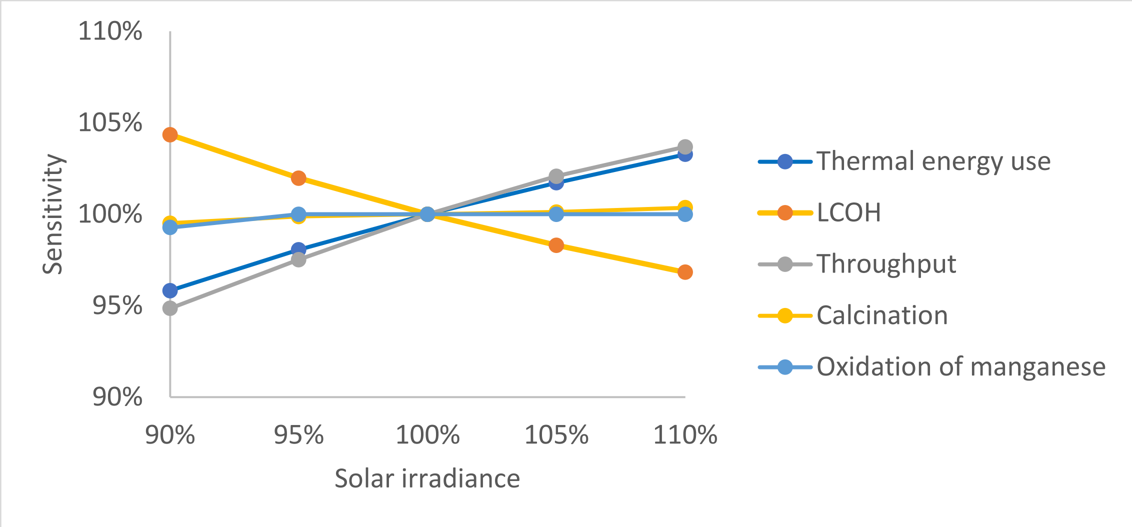

Figure 4. *Sensitivity of productivity, product grade and LCOH to changes in annual solar irradiance.*

A 10 % reduction in annual solar irradiance resulted in 4 % reduction in thermal energy use, while a 10% increase resulted in only a 3 % increase in thermal energy use. This is due to the fact that the process was designed at a solar multiple of 1.5. A change in solar irradiance will not affect the flux to the receiver if the total flux is already above 1700 kW/m^2. This leads to the energy use and also the throughput of the material being more sensitive to reduction in solar irradiance than increased solar irradiance.

The extent of calcination and the oxidation values of manganese in the product serve as indicators of the product quality. It is reassuring to see that even a 10 % drop in annual solar irradiance leads to only a 0.5 % reduction in calcination and a 0.7 % reduction in oxidation of manganese. For increased solar irradiance, the oxidation of manganese remained constant, while calcination improved slightly 0.4 %. This shows that the product quality is insensitive to the changes in annual solar irradiance.

Since the CAPEX for the plant remains the same, the LCOH was influenced by the thermal energy used. For increased solar irradiance, the amount of energy in excess of demand increases and this leads to the LCOH being less sensitive to increased solar irradiance than to decreased solar irradiance.

3.2 Analysis of sensitivity of LCOH to changes in financial model

The capital expenditure (CAPEX) contributes greatly to the LCOH in the financial model. A breakdown of the contributions of different components to the CAPEX is given in the Figure 5. The heliostat field has the largest contribution to the CAPEX and was used to illustrate the sensitivity of the LCOH to CAPEX changes.

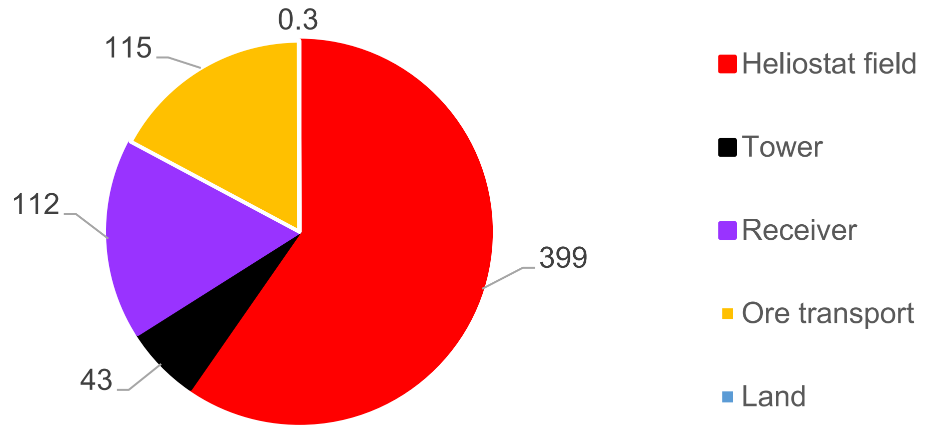

Figure 5. *Component estimated capital expenditure in kUS$.*

The results of the sensitivity analysis of LCOH to changes in the heliostat field cost and interest rates are shown in Figure 6. The baseline interest rate was 7 %.

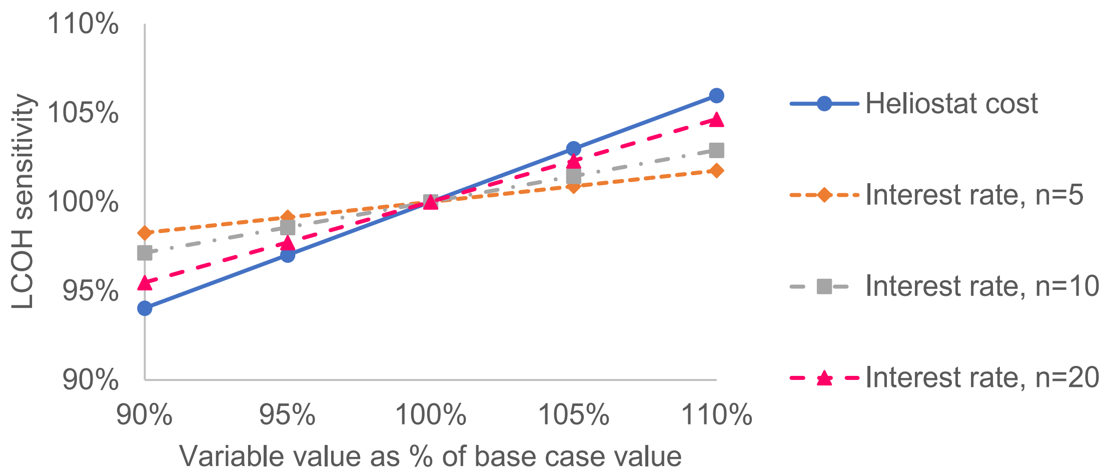

Figure 6. *Sensitivity of LCOH to changes in heliostat field costs and interest rates. The payback period, n, is varied as well.*

The LCOH sensitivity is directly proportional to the heliostat field cost by a factor of 0.6. Heliostat field cost reductions will reduce the LCOH significantly and is therefore important when considering evaluating further cost reduction measures.

4. Conclusion

The concept of direct solar thermal heating of manganese ores has previously been found to produce a product with significantly lower energy requirements for smelting. The direct solar heating of manganese ores was found to be cost competitive with electric heating from the South African grid as well as estimates of electric heating using standalone solar PV.

A sensitivity analysis was done to investigate the influence of deviations in annual DNI on productivity and product quality of the treatment as well as on the LCOH. The LCOH and thermal energy use of the with a 10 % decrease in annual solar irradiance resulting in a 5 % increase in LCOH and a 5 % reduction in productivity. The calcination and manganese oxidation level were insensitive to changes in the annual solar irradiance, indicating that product quality was unaffected.

Further sensitivity analysis investigated the sensitivity of the LCOH to changes in inputs to the financial model. The results found that the LCOH was most sensitive to the heliostat field cost as the major contribution to CAPEX. The LCOH was to a lesser extent sensitive to the interest rate.

The direct heating of manganese ores appears to be a promising alternative to sintering as a pretreatment method for manganese ores containing significant (>20%) amounts of carbonate minerals. The energy efficiency of the process could be improved by heat recovery of the hot product to preheat feed to the solar receiver. The TRL for this pretreatment level is however very low (TRL 2) and significant work is needed to confirm its scalability.

Thermal storage has not been considered in this study, as the assumption is that this treatment will take place near the manganese mine, also realising transport savings due to the reduction in product weight compared to the untreated material (20 – 30 %).

The fine particle size of the product (1 mm diameter particles) is required by the assumption of using the centrifugal solar receiver. As most smelters require particles >6mm, the treated material may be incorporated into briquettes already being produced to recycle dust and metallic fines to the smelter[20]. But, due to the low volatile content of the product, small amounts of the material may be acceptable as direct feed to the smelters and could be a topic for further investigations [10], [21].

It is also recommended that other particle heating receivers be investigated for this concept to find the most suitable design. The current selection of the centrifugal receiver was based on its demonstrated heating capacity, throughput rating and availability of published data for validation of the reactor model.

The next steps in commercializing this concept would be to perform material flow characteristic tests with the manganese ores to confirm their suitability for use in the proposed reactor or to investigate alternative direct solar heating technologies such as beam down facilities with high-temperature belts. Additional scenario analysis may also be performed to investigate the co-location of direct solar thermal treatment with a ferromanganese smelter. Some studies has already been published for co-location of indirect heating of manganese ore [22], [23], [24] (albeit to a lower temperature of 600 °C) and evaluation of the different solar thermal treatment options would be interesting.

Data availability statement

Data supporting the results of the article is available from the author on request.

Author contributions

The author had no co-authors in this paper.

Competing interests

The authors declare that they have no competing interests.

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