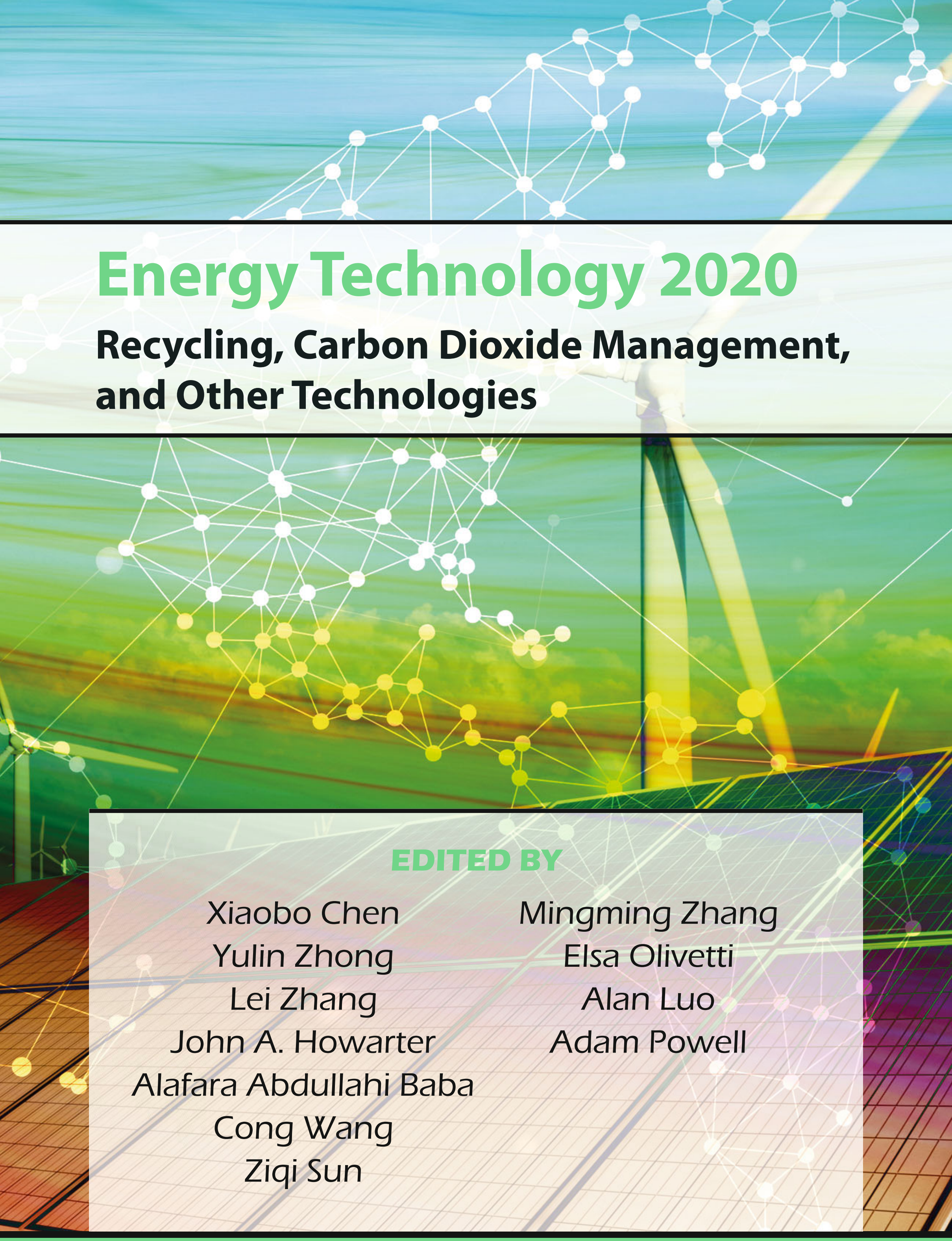

Energy Technology 2020

Recycling, Carbon Dioxide Management, and Other Technologies

EDITED BY

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The Minerals, Metals & Materials Series

Xiaobo Chen · Yulin Zhong · Lei Zhang ·
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Editors

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ISSN 2367-1181 ISSN 2367-1696 (electronic)
The Minerals, Metals & Materials Series
ISBN 978-3-030-36829-6 ISBN 978-3-030-36830-2 (eBook)
https://doi.org/10.1007/978-3-030-36830-2

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Preface

This volume contains selected papers presented at two symposia organized in conjunction with the TMS 2020 Annual Meeting & Exhibition in San Diego, California, USA:

- Energy Technologies and CO_2 Management (sponsored by the TMS Energy Committee)
- Recycling of Secondary, Byproduct Materials and Energy (sponsored by the TMS Recycling and Environmental Technologies Committee)

The papers in this volume intend to address the issues, intricacies, and the challenges relating to energy and environmental sciences.

The Energy Technologies and CO_2 Management Symposium was open to participants from both industry and academia and focused on energy efficient technologies including innovative ore beneficiation, smelting technologies, recycling, and waste heat recovery. Topics cover various technological aspects of sustainable energy ecosystems and processes that improve energy efficiency, reduce thermal emissions, and reduce carbon dioxide and other greenhouse emissions. Papers addressing renewable energy resources for metals and materials production, waste heat recovery and other industrial energy efficient technologies, new concepts or devices for energy generation and conversion, energy efficiency improvement in process engineering, sustainability and life cycle assessment of energy systems, as well as the thermodynamics and modeling for sustainable metallurgical processes are included. This volume also includes topics on CO_2 sequestration and reduction in greenhouse gas emissions from process engineering, sustainable technologies in extractive metallurgy, as well as the materials processing and manufacturing industries with reduced energy consumption and CO_2 emission. Contributions from all areas of non-nuclear and non-traditional energy sources, such as solar, wind, and biomass, are also included in this volume.

The Recycling of Secondary, Byproduct Materials and Energy Symposium provided a forum for papers exploring the valorization of materials and their embodied energy including byproducts or coproducts from ferrous and non-ferrous industries, batteries, electronics, and other complex secondary materials. Although most recycling only involves mechanical and physical manipulation of matter, which typically require one to two orders of magnitude less energy than the chemical manipulation involved in primary production, recycling processes still require energy to operate, and they do not run emission-free. Recycling processes must be designed to deal with materials that are potentially quite different from the original base material. However, there has been a significant mismatch between the technical needs for responsible treatment of secondary, byproduct materials, and embodied energy of materials and the ability to achieve economically feasible and sustainable operations. These materials and their embodied energy are generally low value and can be quite complex due to the significant variation in properties leading to potential mismatch among complexity, regulations, and available resources. The papers included in this volume can provide readers a broad perspective on both the technical as well as policy-based challenges.

We hope this volume will serve as a reference to materials scientists and engineers as well as metallurgists for exploring innovative energy technologies and novel energy materials processing.

We would like to acknowledge the contributions from the authors of the papers in this volume, the effort of the reviewers involved with the manuscripts review process, and the help received from the publisher. We also acknowledge the organizers of both symposia contributing the papers to this volume.

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Xiaobo Chen, RMIT University
Yulin Zhong, Griffith University
Lei Zhang, University of Alaska Fairbanks
John A. Howarter, Purdue University
Alafara Abdullahi Baba, University of Ilorin
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Recycling of Secondary, Byproduct Materials and Energy Symposium Organizers

Mingming Zhang, ArcelorMittal Global R&D
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Alan Luo, The Ohio State University
Adam Powell, Worcester Polytechnic Institute

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Part I Energy Technologies and CO_2 Management Symposium

Part II Recycling of Secondary, Byproduct Materials and Energy

About the Editors

Xiaobo Chen was awarded a Ph.D. in Materials Science and Engineering from Deakin University (2010), worked as a postdoctoral research fellow and ARC DECRA senior research fellow at Monash University (2009–2017), and now is a vice chancellor senior research fellow in the School of Engineering at RMIT University, Melbourne, Australia. His research is multidisciplinary and spans from chemistry and materials science to corrosion, electrochemistry, and biomaterials. His research aims to provide functional characteristics of the surface of light metals to satisfy a large range of engineering applications in automotive, 3C, and biomedical industries.

Yulin Zhong completed his Ph.D. in Chemistry (2010) at the National University of Singapore (NUS) and did his postdoctoral training at Princeton University, Massachusetts Institute of Technology, and Monash University. He was awarded an ARC DECRA fellowship in 2014 and joined Griffith University as a senior lecturer in 2016. His research group interests include electrochemical production of 2D nano-materials, 3D printing, smart windows, and wearable devices.

Lei Zhang is an associate professor in the Department of Mechanical Engineering at the University of Alaska Fairbanks (UAF). Prior to joining the UAF, She worked as a postdoctoral associate in the Department of Chemical and Biomolecular Engineering at the University of Pennsylvania. She obtained her Ph.D. degree in Materials Science and Engineering from Michigan Technological University in 2011, and her M.S. and B.E. degree in Materials Science and Engineering from China University of Mining and Technology, Beijing, China, in 2008 and 2005, respectively. Her current research mainly focuses on the synthesis of metal-organic frameworks (MOFs) and MOF-based nano-composites, and the manipulation of their properties and applications in gas storage, separation, and water treatment. She is also working on the development and characterization of anti-corrosion coatings on metallic alloys for aerospace and biomedical applications.

She has served on the TMS Energy Committee since 2014, including the vice-chair role in 2018–2019, and served on a Best Paper Award Subcommittee of the committee. She has served as a frequent organizer and session chair of TMS Annual Meeting symposia (2015–present). She was the recipient of the 2015 TMS Young Leaders Professional Development Award.

John A. Howarter is an associate professor in Materials Engineering at Purdue University with a joint appointment in Environmental & Ecological Engineering. His research interests are centered on synthesis, processing, characterization, and end-of-life fate of sustainable polymers and nano-composites. His research impacts water treatment, thermal management in electronic devices, and material design for recycling and value recovery. He has been involved in the Public and Governmental Affairs (P&GA) Committee of TMS, serving as the chair from 2017 to 2020. Dr. Howarter earned a B.S. from The Ohio State University in 2003 and Ph.D. from Purdue University in 2008, both in Materials Engineering. From 2009 to 2011, he was a National Research Council postdoctoral scholar in the Polymers Division of the National Institute of Standards and Technology in Gaithersburg, Maryland.

Alafara Abdullahi Baba is a professor of Analytical/Industrial and Materials Chemistry in the Faculty of Physical Sciences, University of Ilorin, Nigeria. He holds a Ph.D. degree in Chemistry from the University of Ilorin in 2008. His dissertation titled Recovery of Zinc and Lead from Sphalerite, Galena and Waste Materials by Hydrometallurgical Treatments was judged the best in the area of Physical Sciences at University of Ilorin, Nigeria, in 2010. Until his current appointment as a head, Department of Industrial Chemistry in 2017, he was a deputy director—Central Research Laboratories, University of Ilorin (2014–2017). He is a fellow of the Chemical Society of Nigeria (FCSN) and Materials Science & Technology Society of Nigeria (FMSN), is currently the secretary of the Hydrometallurgy and Electrometallurgy Committee of the Extraction and Processing Division (EPD) of The Minerals, Metals & Materials Society (TMS), is a co-organizer of the Rare Metal Extraction & Processing Symposium and Energy Technologies & Carbon Dioxide Management Symposium at the TMS Annual Meeting and Exhibition, and is on the TMS Materials Characterization, Education, and EPD Awards committees.

He has keen interest in teaching, community services, and research covering solid minerals and materials processing through hydrometallurgical routes; reactions in solution and dissolution kinetic studies; and preparation of phyllosilicates, porous, and bio-ceramic materials for industrial value additions. He has 113 publications in nationally and internationally acclaimed journals of high impact, and has attended many national and international workshops, conferences, and research exhibitions to present his research breakthroughs. He is the recipient of several awards and honors including 2015 MISRA AWARD of the Indian Institute of Mineral Engineers (IIME) for the best paper on Electro-/Hydro-Bio-Processing at the IIME International Seminar on Mineral Processing Technology—2014 held at Andhra University, Visakhapatnam, India; 2015 MTN Season of Surprise Prize as Best Lecturer in the University of Ilorin—Nigeria category; Award of Meritorious Service in recognition of immense contributions to the

Development of the Central Research Laboratories, University of Ilorin, Nigeria (2014–2017); and 2018 Presidential Merit Award in Recognition of Passion, Outstanding and Selfless Service to the Materials Science and Technology Society of Nigeria.

Cong Wang is a professor in the School of Metallurgy, Northeastern University, China. Prior to joining the faculty of his alma mater, he worked in Northwestern University, Saint-Gobain, and Alcoa, all in the USA. He obtained his Ph.D. from Carnegie Mellon University, M.S. from Institute of Metal Research, Chinese Academy of Sciences, and B.S. (with honors) from Northeastern University. He is now leading a group dedicated to oxide metallurgy.

He is an active member and a prolific scholar in the global metallurgy community. He has been recognized with distinctions such as TMS Early Career Faculty Fellow Award, CSM Youth Metallurgy S&T Prize, Newton Advanced Fellowship, JSPS Invitational Fellowship, TÜBİTAK Fellowship, SME Outstanding Young Manufacturing Engineer Award, and ASM Silver Medal. He serves as a key reader and vice-chair for the Board of Review for *Metallurgical and Materials Transactions B*; review editor for *Journal of Materials Science and Technology*; editorial board member of *International Journal of Refractory Metals and Hard Materials* and *Journal of Iron and Steel Research, International*; and corresponding expert for Engineering. He chaired the TMS Energy Committee from 2016 to 2017. He is the inaugural chair for the ASM Shenyang Chapter, and faculty advisor for Material Advantage Northeastern University. He initiated the International Metallurgical Processes Workshop for Young Scholars (IMPROWYS) and organized major conferences/symposia of technical significance.

Ziqi Sun is currently an associate professor and ARC future fellow in the Queensland University of Technology (QUT), Australia. His research interest includes developing bio-inspired smart nano-materials and 2D metal oxide nano-materials for sustainable energy and environmental applications, such as rechargeable batteries, oil-water separations, and catalysis. He received his Ph.D. degree in Materials Science and Engineering from the Institute of Metal Research, Chinese Academy of Sciences in 2009. After one year of experience as the NIMS postdoctoral fellow (Japan) on solid oxide fuel cells, he joined the University of Wollongong (UOW), Australia, in 2010 and moved to QUT as a faculty member in 2015. He has served in some prestigious leadership roles in both the academic and professional communities, such as the chair of the TMS Energy Committee; Editor-in-Chief of *Sustainable Materials and Technologies* (CiteScore = 8.43, Elsevier); handling editor of *Physics Open* (Elsevier); principal editor of *Journal of Materials Research* (MRS); associate editor of *Surface Innovations* (ICE); and editorial board member of *Scientific Reports*, *Journal of Materials Science and Technology*, and *Nano Materials Science*.

Mingming Zhang is a lead research engineer at ArcelorMittal Global R&D in East Chicago, Indiana. He has more than 15 years of research experience in the field of mineral processing, and metallurgical and materials engineering. He obtained his Ph.D. degree in Metallurgical Engineering from The University of Alabama and his master's degree in Mineral Processing from General Research Institute for Non-ferrous Metals in China. Prior to joining ArcelorMittal, he worked with Nucor Steel in Tuscaloosa, Alabama, where he was a metallurgical engineer leading the development of models for simulating slab solidification and secondary cooling process. He has conducted a number of research projects involving mineral beneficiation, thermodynamics and kinetics of metallurgical reactions, electrochemical processing of light metals, metal recycling, and energy efficient and environmentally cleaner technologies. He has published more than 50 peer-reviewed research papers, and he is the recipient of several US patents. He also serves as editor or reviewer for a number of prestigious journals including *Metallurgical and Materials Transactions A* and *B*, *JOM*, *Journal of Phase Equilibria and Diffusion*, and *Mineral Processing and Extractive Metallurgy Review*. He has made more than 30 research presentations at national and international conferences including more than ten keynote presentations. He was the recipient of the 2015 TMS Young Leaders Professional Development Award. He has served as a conference/symposium organizer and technical committee chair in several international professional organizations including The Minerals, Metals & Materials Society (TMS), Association for Iron & Steel Technology (AIST), and the Society for Mining, Metallurgy & Exploration (SME).

Elsa Olivetti is the Atlantic Richfield associate professor of Energy Studies in the Department of Materials Science and Engineering at the Massachusetts Institute of Technology (MIT). Her research focuses on improving the environmental and economic sustainability of materials using methods informed by materials economics, machine learning, and techno-economic analysis. She has received the NSF Career award for her experimental research focused on beneficial use of industrial waste materials. She received her B.S. degree in Engineering Science from the University of Virginia. Her Ph.D. in Materials Science and Engineering from MIT was focused on the development of cathode materials for lithium ion batteries.

Alan Luo is a professor of Materials Science and Engineering and Integrated Systems Engineering (Manufacturing) at The Ohio State University (OSU) in Columbus, OH, USA. He is also the director of OSU Light Metals and Manufacturing Research Laboratory (LMMRL) and on the steering board of OSU Center for Simulation Innovation and Modeling (SIMCenter). He is an elected fellow of American Society of Metals (ASM) International and Society for Automotive Engineers (SAE) International. He served on the Board of Directors of TMS (The Minerals, Metals & Materials Society) and as chair of its Light Metals Division. He is also a director of the board of

International Magnesium Association (IMA) and serves as chair of its annual conference program chair. He is a past chair of SAE Materials Engineering Activities. He has 20 patents and more than 240 technical publications on advanced materials and manufacturing, specializing in lightweight materials and applications.

Prior to joining OSU in July 2013, He was a GM technical fellow at General Motors Global Research and Development Center (Warren, MI, USA) with 20 years of industrial experience. He has 20 patents and more than 240 technical publications in advanced materials, manufacturing, and applications. He won two John M. Campbell Awards for his fundamental research, and three Charles L. McCuen Awards for research applications at GM. Over the years, he has received the TMS Brimacombe Medalist Award, SAE Forest R. McFarland Award, United States Council for Automotive Research (USCAR) Special Recognition Award, ASM Materials Science Research Silver Medal, and International Magnesium Association (IMA) Award of Excellence in cast projects. His research is also recognized by several Best Paper awards from TMS, SAE, and AFS (American Foundry Society).

His research in sustainable energy and sustainable resources includes (1) lightweight materials (aluminum, magnesium, titanium and high-entropy alloys, bio-metals, super-wood, and metal matrix nano-composites); (2) advanced manufacturing processes (casting, forming, additive, and multi-material manufacturing); and (3) lightweight design and integrated computational materials engineering (ICME).

Adam Powell is an associate professor in the Mechanical Engineering department who joined the WPI faculty in August 2018. His field is materials processing, and research focuses on validated mathematical modeling of metal process development for clean energy and energy efficiency. His research group is developing new projects whose goals are to reduce vehicle body weight, lower solar cell manufacturing cost with improved safety, reduce or eliminate environmental impact of aerospace emissions, and improve grid stability with up to 100% clean energy.

His research has resulted in 68 publications across materials classes: metal extraction/refining and product development, thin films, ceramic coatings, polymer membranes, batteries, and electromagnetic propulsion. He is the author of nine open-source computational tools in materials processing, microstructure, and thermodynamics modeling.

Part I

Energy Technologies and CO_2 Management Symposium

The Impact of Solar Resource Characteristics on Solar Thermal Pre-heating of Manganese Ores

Lina Hockaday, Tristan McKechnie, Martina Neises von Puttkamer and Matti Lubkoll

Abstract The proposed paper evaluates an alternative ferromanganese production flowsheet seeking to pre-heat manganese ores with concentrating solar thermal energy to 600 °C. The benefits of solar thermal pre-heating will be evaluated based on a cost discounted economic model taking into account the variability of the solar resource, capital costs, and operating costs of a solar thermal plant over the lifetime of the project. Solar variability will be discussed based on possible implementation sites for such technologies, and the cost and benefits of thermal storage in the flowsheet will also be evaluated. This work is part of the PreMa project, aiming to advance novel energy systems in the drying and pre-heating of furnace materials. The PreMa project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 820561.

Keywords Concentrating solar thermal · Pre-heating · Ferromanganese production

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X. Chen et al. (Eds.), *Energy Technology 2020: Recycling, Carbon Dioxide Management, and Other Technologies*, The Minerals, Metals & Materials Series,
https://doi.org/10.1007/978-3-030-36830-2_1

Introduction

Manganese is an important additive to steel. Manganese content in steel improves toughness and wear resistance of steel, and on average about 0.8% manganese is added to steel. 90% of manganese is used as steel additive in the form of ferromanganese alloys. Ferromanganese alloys are produced in either blast furnaces or electric arc furnaces with carbon as a reductant. Detailed description of manganese ferroalloy production, both for high carbon ferromanganese and low carbon silicomanganese alloys can be found in literature [11, 19]. Global manganese ore mine production is summarized in Table 1 as adapted from [21]. The Republic of South Africa (RSA) is the leading producer of manganese ores and has the largest land based manganese ore reserves.

Global manganese ferroalloy production which includes different grades of ferromanganese and silicomanganese is given in Table 2 as adapted from [10].

The PreMa project [17] aims to investigate the optimal pre-heating option for a high carbon ferromanganese furnace in order to reduce electricity consumption and greenhouse gas emission from manganese ferroalloy production [8]. Although

Table 1 Global mine production and reserves of manganese ores by country, manganese content

Year	Unit	RSA	Ukraine	Brazil	Australia	Gabon	China	Other	World total
2017	kt/a	5400	735	1160	2820	2190	1700	1278	17,300
2018	kt/a	5500	740	1200	3100	2300	1800	1342	18,000
Reserves	kt	230,000	140,000	110,000	99,000	65,000	54,000	62,000	760,000

Table 2 Manganese ferroalloy production by country, based on manganese content. China was the largest manganese ferroalloy producer, with production being four times more than India and ten times more than South Africa. Norway and Spain were the largest European producers of manganese ferroalloys

Country	Production (000 mt)
China	10,349
India	2372
RSA	741
Ukraine	713
South Korea	686
Norway	608
Japan	483
Russia	352
Australia	254
Spain	243
Other	1447
World total	18,249

the project also investigates pre-heating with furnace off-gas, bio-carbon, and fossil carbon, this paper focuses on the novel use of concentrating solar thermal energy as the energy source for pre-heating. The cost of using concentrating solar thermal process heat is dependent on the available solar resource at the location it is captured, as well as the technology choices selected. This paper studies three possible locations for concentrating solar thermal plants in proximity to current manganese ferroalloy smelters, as well as one location near manganese ore mines. It was attempted to select locations with existing smelters and good solar radiation in Europe, Africa, and China. The locations selected for evaluation are listed below. These locations were not selected as ideal sites, for example China has locations with better solar resources in the Inner Mongolia Province, but is evaluated to provide insight into the factors involved in the application of solar thermal process energy to a high-temperature industrial process.

- Jiayuguan, Gansu Province, China
- Huesca, Spain
- Hotazel, Northern Cape Province, South Africa (RSA 1)
- Emalahleni, Mpumalanga Province, South Africa (RSA 2).

Manganese Ferroalloy Production Process Modeling

To investigate the energy demand for pre-heating of manganese ores, a HSC model [14, 15], Version 9.9.2.3, was constructed for the PReMA project. The HSC model is based on the possible reactions that can take place during pre-heating and smelting and the extent they progress towards completion.

Traditional pre-heating systems rely on fossil fuel combustion, and a reducing atmosphere with low partial pressures of oxygen is generally practiced [20]. The novel solar thermal pre-heating unit relies on heated air, maintaining an oxidative atmosphere in the unit, and therefore, the reactions differ from those expected in a reducing atmosphere and are given in Eqs. 1–8. Equation 7 is the Boudouard reaction where carbon dioxide reacts with carbon to form carbon monoxide. This reaction is likely to start taking place at temperatures above 500 °C and to proceed fully only at temperatures above 800 °C. Similarly, this preliminary investigation has been guided by calculated equilibrium reactions for the thermal decomposition of MnO_2 to Mn_2O_3

Table 3 Illustrative modeling assumptions and resulting energy demand for the pre-heater

Reaction	1	2	3	4	5	6	7	8
Completion (%)	100	80	100	100	100	100	0	100

Pre-heating target, °C	600
Pre-heater energy demand, kWh/t feed	339.8
Process CO_2 emission factor, t/t alloy	2.31

as published by [19, p. 74]. Future work will involve the determination of kinetics for these reactions. The completion of these reactions will influence the final energy demand of the pre-heater, and values in Table 3 are for illustrative purposes only.

The results from process modeling for pre-heating to 600 °C are shown in Table 3. The process CO_2 emission factor of 2.31 is a reduction in 7% on the emissions factor for a process not employing pre-heating. The energy demand for a pre-heater feeding a 30MW high carbon ferromanganese furnace that requires a manganese ore feed of approximately 40t/h will therefore have an energy demand of 13.6MW to achieve a product temperature of 600 °C. Due to the variable nature of the solar resource, a solar thermal plant will only be able to meet this demand in part. The following section describes the methodology to size a solar thermal plant, with thermal storage to improve availability and electrical heating as back-up for the four different locations identified as possible sites. Electrical heating was chosen as back-up technology due to the increase in zero emission electricity options available to industry [16]. Using electricity as back-up rather than a fossil fuel also prevents pre-heating cycling between an oxidizing and a reducing environment, which may lead to problems with control of the carbon balance in the submerged arc furnace (SAF).

$$MgCO_3 \longrightarrow MgO + CO_2(g) \tag{1}$$

$$CaMg(CO_3)_2 \longrightarrow MgO + CaCO_3 + CO_2(g) \tag{2}$$

$$H_2O(l) \longrightarrow H_2O(g) \tag{3}$$

$$2FeO \cdot OH \longrightarrow Fe_2O_3 + H_2O(g) \tag{4}$$

$$MnCO_3 \longrightarrow MnO + CO_2(g) \tag{5}$$

$$2AlO(OH) \longrightarrow Al_2O_3 + H_2O(g) \tag{6}$$

$$C + CO_2(g) \longrightarrow CO_2(g) \tag{7}$$

$$4MnO_2 \longrightarrow 2Mn_2O_3 + O_2(g) \tag{8}$$

Solar Thermal Plant Modeling Methodology

In recent years, solar thermal technology has advanced through the development of solid particle receivers [5, 6]. Solid particle receivers operate with the solid particles directly exposed to the concentrating solar flux. The layer of solid particles in the Centrec® receiver shields the rotating structure of the receiver and makes possible particle temperatures in excess of 900 °C [2]. Figure 1 shows a schematic of a CST plant that would provide high-temperature process heat to an industrial process as envisaged in the PreMa project [17].

The purpose of this section is to compare the effect of solar resource variability on the potential for incorporating concentrating solar thermal (CST) technologies in manganese ore pre-heating. The integration of CST technologies is envisioned to lead to lower energy costs and significant reductions in carbon emissions, as already presented in Section Manganese Ferroalloy Production Process Modeling. The CST

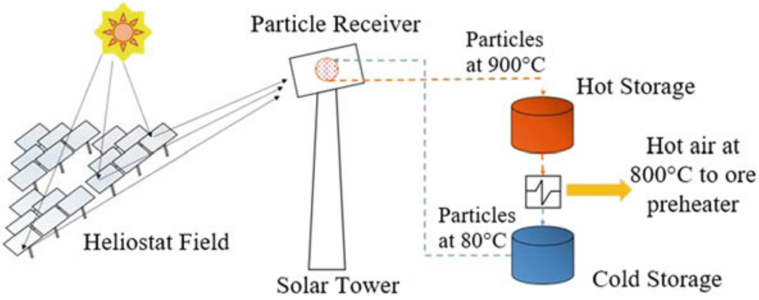


Fig. 1 Concentrating solar thermal technologies

plant model assumes the German Aerospace Center's (DLR) particle receiver technology [2], CentRec®, for receiver and thermal energy storage. For the purpose of this assessment, their receiver sizing and performance characteristics are based on [1]. The model follows [12] with the thermal receiver size fixed at 1 m^2 and 2.5 MW_t output. The solar field is then sized to provide a system output of 2.5 MW_t at solar equinox. Each such CST tower system can then at best provide 2.5 MW_t peak to a consumer. Multiple CST towers are foreseen to be deployed when the heat demand exceeds the supply of one tower. The lowest levelized cost of heat, LCOH, of a CST system is usually found with the solar components being significantly over-sized compared to the thermal demand. This over-sizing permits thermal storage and is expressed through the solar multiple, defined as follows:

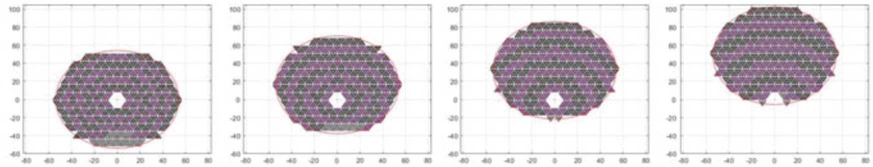
$$\mathrm{SM} = \frac{Q_{\mathrm{rec}}}{Q_{\mathrm{process}}}, \tag{9}$$

where Q_{rec} is the thermal output of the receiver at the solar field design point, and Q_{process} is the thermal output to process.

The solar plant annual performance assessment is conducted by modeling at hourly steady state conditions. The solar resource data is obtained as typical meteorological year (TMY) from Meteonorm [13], Version 7.3. Details regarding the plant and economic modeling and model inputs are explained further in the paper of [12]. The solar plant operation was simulated to determine the energy produced, from which the LCOH was determined. A parametric study was then performed to determine the most suitable solar plant configuration to obtain the lowest LCOH for each site.

Field Layout

The positioning of the tower within the heliostat field was investigated, resulting in improved optical efficiency for the solar field. This is an improvement on the



(a) Tower at center (b) Tower at 30% (c) Tower at 60% (d) Tower at 90%

Fig. 2 Tower position optimization

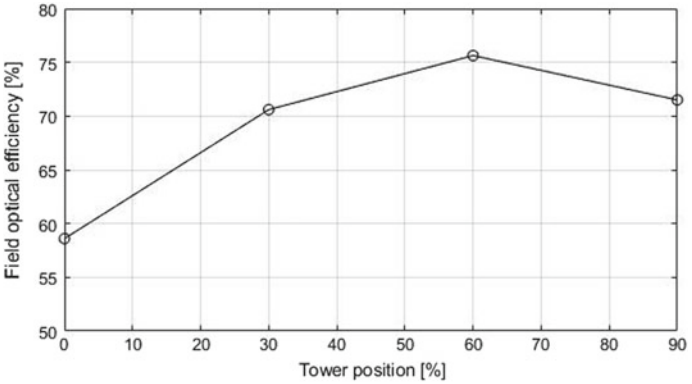


Fig. 3 Tower position within field and resulting field optical efficiency

methodology described by [12]. The receiver is modeled angle downward 45° from the horizontal. This allows heliostats placed behind the tower to have line of sight to the receiver opening. Heliostats placed near and behind the tower have improved optical efficiency compared to heliostats in front of the tower but further away. The optimal placement of the tower within the field was determined as presented in Fig. 2. Figure 3 shows the resulting field optical efficiency. It can be seen that the tower placed at $0.6 \times r_{\text{field}}$ from the center of the field resulted in the maximum field optical efficiency. These results agree with those of [7]. All fields sized in this paper will therefore have a layout similar to Fig. 2c. The specification of the heliostat field now allows the capacity factor (CF) to be calculated. The capacity factor is defined as the average annual energy production divided by the process heat demand.

Operating Strategy

The configuration of a CST plant producing heat at the lowest levelized cost of heat, LCOH, does not typically have a 100% capacity factor; for this reason back-up electric heaters are included as auxiliary heating for when solar heat is insufficient to meet demand. LCOH is determined by dividing the total costs over the project lifetime

Table 4 Plant locations and resulting solar fields

Location		Units	RSA 1	RSA 2	Spain	China
Site data	Latitude	–	27.240 S	25.886 S	41.926 N	39.897 N
	Longitude	–	22.902 E	29.123 E	0.183 E	98.318 E
	DNI	kWh/(m^{2}a)	2795	2117	1929	1520
Solar plant specifications	h_{tower}	m	40			
	a_{rec}	m^2	1			
	α	°	45			
	η_{rec}	%	90			

by the total amount of energy supplied over the lifetime of the project. A combined LCOH of solar electric heating was calculated to determine the configuration of the solar plant that results in the lowest produced combined solar electric heat. The cost of electrically generated heat is simplified as the cost per MWh of electricity. The combined solar electric LCOH was calculated as follows:

$$\text{LCOH}_{\text{comb}} = \frac{\text{LCOH}_{\text{CST}}\text{Q}_{\text{CST}} + \text{LCOH}_{\text{el}}\text{Q}_{\text{el}}}{\text{Q}_{\text{tot}}}, \tag{10}$$

where Q_{CST} is the total annual solar generated heat, Q_{el} is the total annual electrical generated heat, Q_{tot} is the total annual generated heat, LCOH_{CST} is the cost of solar generated heat and LCOH_{el} is the cost of electrically generated heat.

The operating strategy for the plant is to deliver the thermal demand whenever the receiver and/or TES has sufficient energy available. At any point when the solar plant does not output the rated thermal demand, then electric heating is supplemented.

Locations

Table 4 shows the locations that were assessed and the common solar plant parameters with DNI data from [18] and solar plant specifications as modeled by [12]. The two South African locations have similar latitudes, but differ in the available solar resource. Likewise for the Chinese and Spanish locations, the solar plant specifications listed are h_{tower} tower height, a_{rec} receiver aperture area, α the receiver tilt angle from the horizontal, and η_{rec} the receiver solar to particle efficiency.

Results and Discussion

Table 5 summarizes the results from the solar plant modeling and parametric studies. The CST parameters are configured for the lowest annual combined LCOH, incorporating solar with electric back-up for constant heat production. $\mathrm{LCOH_{CST,pot}}$ represents an optimized CST only plant configuration and provides reference of the lowest possible solar LCOH. Relative to this, the configuration represented by $\mathrm{LCOH_{CST}}$ has significantly higher solar capacity factor to reduce the $\mathrm{LCOH_{comb}}$ by suppressing electricity usage. The economic benefit of increasing the solar capacity factor is more than the added cost for a larger CST systems. This is because for all locations, CST heat is more affordable than electrical heat.

Locations with similar latitudes (RSA 1 and RSA 2, and Spain and China) experience similar sun angles throughout the year. As the solar fields are sized for all locations with a common design point DNI, the locations with similar latitudes therefore have similar sized fields. Further, the annual solar field efficiency can be seen to have increased compared to the results from [12], as the tower has been located at an improved location.

The Spanish and Chinese locations can be seen to have significantly more expensive electricity, and therefore, favor systems with higher SM and TES size, thereby off-setting the amount of electricity required. Even then, the Chinese location shows relatively moderate CF due to the poor direct normal irradiance (DNI). The South African locations feature less storage, nonetheless show high CF due to high solar resources. RSA 1 is able to achieve a high capacity factor as the solar resource for the location is excellent. RSA 2's solar plant configuration is not further over-sized as the electricity cost is relatively low.

All locations benefit from incorporating CST technologies. The higher the electricity tariff for a location, the larger the solar system will be to suppress electricity use. The benefit of the solar with electric back-up compared to total electrification is shown in the final row of Table 5. Electricity cost data for South Africa was obtained from [4], for Spain from [9], and for China from [3]. The benefit of solar thermal heating as compared to electrification is of course larger for countries with higher electricity costs such as Spain. It should be noted that the cost savings will increase with electrical tariff increases; whereas, the solar heat cost will remain steady over the life of the system. The model in this paper does not include electricity price escalation.

Conclusion

This paper evaluated the energy demand for a pre-heater driven by a solar thermal plant providing hot air and backed up by electric heating elements. The aim of the study was to investigate the feasibility of high-temperature solar thermal process heat for pre-heating as a cost effective alternative to electrification of the process as a way of limiting green house gas emissions. The results confirmed that the combined solar

Table 5 Solar plant configuration

Type	Parameters	Units	RSA 1	RSA 2	Spain	China
Site data:	DNI	$kWh/(m^2a)$	2795	2117	1929	1520
	$LCOH_{el}$	\$/MWh	47.29	47.29	115.51	74.65
CST potential:	$LCOH_{CST,pot}$	\$/MWh	35.48	43.43	46.28	56.02
Combined system per tower:	TES	h	14	14	22	16
	A_{sf}	m^2	3563	3563	3616	3616
	$\eta_{sf,a}$	%	65	66	62	62
	SM	–	3.2	3.0	4.5	4.2
	$\dot{Q}_{process}$	MW	0.79	0.82	0.55	0.60
	CF_{CST}	%	79	63	76	63
	$LCOH_{CST}$	\$/MWh	36.25	43.85	54.02	57.46
	$LCOH_{comb}$	\$/MWh	38.55	45.13	68.98	63.75
For pre-heater integration:	Number of towers	–	18	17	28	23
	Total heliostat field area	ha	6.4	6.1	9.1	8.3
Benefit versus total electrification	$\Delta LCOH^a$	%	19	5	40	17

[a] $\Delta LCOH = (LCOH_{el} - LCOH_{comb})/LCOH_{el}$

thermal and electric heating produced lower energy costs over a project lifetime of 25 years compared to heating through electrification only for all locations evaluated. Locations with a high annual DNI had lower levelized energy costs than locations with lower annual DNI levels, but the cost of electricity at each location also had an influence on the solar thermal plant design. High electricity costs increased the amount of thermal energy storage and the solar multiple to ensure that the most cost effective solution has a high solar share. Countries with high annual DNI and low electricity costs may in future have a global competitive advantage for low emission, high-temperature process energy applications.

The methodology was optimised for heliostat field size, tower position, solar multiple (SM), and thermal energy storage (TES) at each location. The optimization resulted in higher capacity factors than previously published [12] for systems that were not optimized to achieve the lowest LCOH.

In conclusion, although combustion heating with fossil fuels such as metallurgical coke and coal remains the least cost alternative at the time of writing, solar thermal process energy can compete favorably with process heating by electrification for projects with a lifetime of 25 years. With industry targets of lowering greenhouse gas emissions becoming more urgent [16], evaluating where solar thermal process energy can be a cost effective alternative is of relevance to industry.

Acknowledgements The PreMa project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 820561. This paper is published with the permission of Mintek.

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