

Concentrated Solar Energy in Iron Production: Towards Zero-Carbon Metallurgy

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Abstract

Given the importance of environmental protection in modern societies, one of the objectives of industrial strategies in general and the metallurgical industries in particular is to find new, ecologically acceptable energy sources. One of these energy sources is solar energy, which, when properly concentrated, has a lot of promise for high temperature applications like those needed in metallurgical operations. In this work, we suggest using focused sun energy to make iron. The agglomeration of iron ore combinations and iron reduction with carbon (and coke breeze) have been studied using concentrated solar thermal energy. The results of the investigations show the usual stages of iron ore sinters and the existence of iron through smelting reduction. This article investigates the possibility of employing concentrated solar energy in iron metallurgy as a sustainable substitute for conventional fossil fuels. The findings point to a viable avenue for cleaner iron production by showing that concentrated solar radiation can efficiently promote the reduction of iron oxides to metallic iron. The report also covers the difficulties and factors to be taken into account when expanding this technology for industrial use, such as financial implications, energy efficiency, and integration with current infrastructure. All things considered, the study makes a strong case for using solar energy in metallurgical processes, which will help create more ecologically friendly and sustainable industrial processes.

Keywords: Concentrated solar energy, iron, direct reduction iron, solar energy, environment

INTRODUCTION

Revolutionizing Iron and Steelmaking with Solar Energy

Iron and steel are necessary commodities, as seen by the production of almost 1600 Mt of crude steel in 2016 alone. Traditional steel production, which is primarily done using blast furnace (BF) and basic oxygen furnace (BOF) methods, is energy-intensive and a significant source of CO₂ emissions, accounting for 4% to 7% of global emissions. While emerging technologies like direct reduced iron (DRI) using reducing gases offer alternatives, they are still small players in the industry [1].

The Potential of Concentrated Solar Energy

For high-temperature activities like welding, ceramic synthesis, and metallurgical operations, concentrated solar energy shows potential. It is not widely used in steelmaking, though. Studies have demonstrated that solar energy can lower emissions, increase steel quality, and lower iron oxides. For example, mill scale has been treated in solar-heated fluidized bed furnaces to produce Fe₃O₄ devoid of contaminants that is appropriate for generating high-quality steel [2].

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Challenges in Steelmaking Emissions

Significant CO₂ emissions are produced during the BF-BOF steel production process, with emissions ranging from 1630 to 1960 kg per ton of

steel. Despite using electricity, electric arc furnaces (EAF) still release 560 to 1450 kg of CO₂ per ton. Replacing coke, a crucial reducing agent and heat source, is a significant problem. The required heat might be produced by concentrated solar energy, which would lessen the need for coke and cut emissions [3].

Solar-Driven Iron Ore Agglomeration

Coke, recycled materials, and fines are heated on a moving grate in the traditional iron ore sintering process. High temperatures (1300–1400°C) are needed for this process, which also produces a significant amount of CO₂. A solar-driven alternative replaces coke combustion with solar heat, achieving agglomeration in a stationary crucible system. Solar heat might preheat materials, reduce iron ores, and start important processes, opening the door for sustainable steel manufacturing even though it does not have the gas flow of industrial sintering.

This creative strategy uses solar energy to revolutionize the iron and steel sector, lowering its carbon footprint and bringing us one step closer to a more environmentally friendly future [4].

MATERIALS AND METHODS

The experiments were conducted in a 1.5 kW vertical axis solar furnace owned by the Centre National de la Recherche Scientifique (PROMES-CNRS) at Odeillo, France. It features a heliostat that follows sunlight and directs it toward a 2.0-meter-diameter parabolic concentrator (Figure 1). The parabolic concentrator forces the radiation to converge in a focal point with a diameter of 15 mm. The maximum concentration that can be reached is 15,000 times the incident radiation. The mixes were positioned beneath the focus point in tabular alumina crucibles that were 3 mm thick, 55 mm tall, 30 mm in upper diameter, and 25 mm in lower diameter (refer to Figure 2a). Depending on the sample, the trials lasted anywhere from 12 to 20 minutes. Throughout the experiment, the sample was kept beneath the focal point. Tests were conducted in an air environment. However, gases and particles emitted during the trials were captured by a glass canopy attached to a pump to prevent them from adhering to the parabolic concentrator (Figure 2b). To ensure reproducibility, the same mixtures were utilized in each of the five tests. The mixes were made with sinter mixture (sinter feed Voestalpine: $d_{50} < 2$ mm) and 2 mass percent of coke breeze. The mixes were charged into the crucible after being manually combined and homogenized. Similar to coke breeze, the Although we only used the fine granulometric fraction, the Dwight-Lloyd machine uses Voestalpine sinter feed in its industrial iron ore sintering process. However, because fluid-dynamics (solid-gas interaction) did not call for it, the sinter mixture was not granulated in our investigations [5–10].



Figure 1. Scheme of the parabolic concentrator.

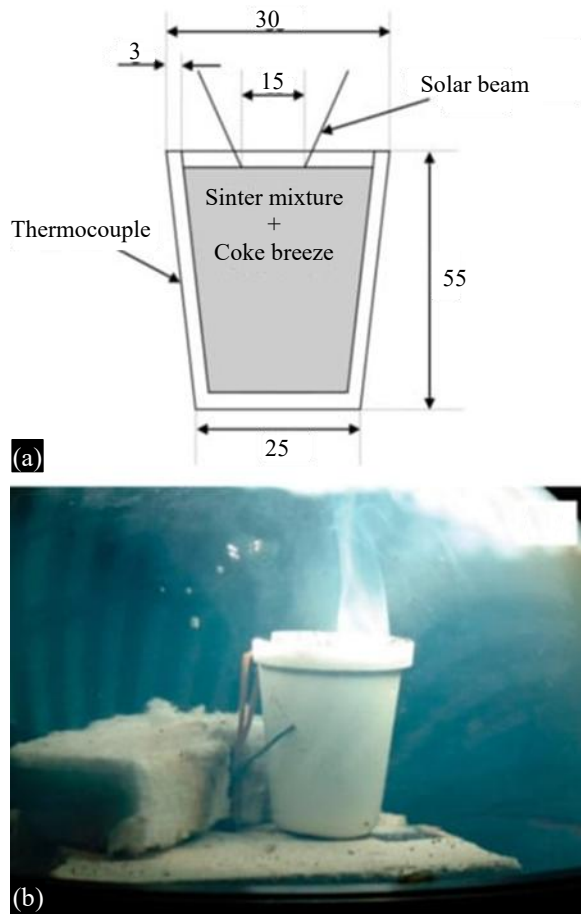


Figure 2. (a) Diagram of the test apparatus, showing distances (b) picture of actual conditions, showing fumes escaping from the sample (black thermocouple wire, at average crucible height).

Iron oxides (FeO and Fe_3O_4) are the most prevalent phases, according to the X-ray diffraction investigations. Calcium silica-ferrites, ferrites, and aluminates are also present in the samples. The crystalline phases were quantitatively analyzed using X Powder12 Ver. 01.02. Power was supplied progressively in order to lessen the projections and heat the mixture for gradual sintering. This would enable the confirmation of the usual sequence of reactions in the industrial sintering process: cold and wet zone ($<100^\circ\text{C}$, which would be significantly short, seconds); cooling zone (recrystallization reactions after the removal of the solar beam); reaction zone (maximum temperatures, $>1400^\circ\text{C}$, reactions involved in the formation of part of the phases detected during the X-ray diffraction analyses); and drying zone ($100\text{--}500^\circ\text{C}$, which in our case would correspond to low power values, moisture vaporization, and dehydration reactions, seconds). Due to the lack of downdraught suction in our solar agglomeration process for iron ore mixes, as was previously noted, the hot gases were unable to flow through the load and fulfill the aforementioned processes in all of the material placed in the crucible.. The fact that the particles that need to aggregate in our tests are less than 2 mm is another factor to take into account. Particles of various sizes are used in the industrial sintering process to create channels that allow gasses to circulate. The flow of gases during the sintering process is really a well-researched parameter, and several sinter bed structure models (such as MEBIOS and RF-MEBIOS) have been examined. In addition to providing a path for gasses to escape during the sintering process, these channels also form an appropriate pore structure for the load that will be placed on the blast furnace later on. Partial melting, which permits the formation of the characteristic sinter phases and establishes the proper structure of voids and pores for the ensuing load in the blast furnace, is one benefit of the industrial sintering process. Unfortunately, not only was downdraught suction not used during our iron

ore agglomeration trials, but partial melting was also not accomplished. At a depth of 12 to 15 mm and on the surface that was in contact with the solar beam, the sample was totally melted. Because some of the material had completely melted, liquid was present, filling up the gaps, destroying the interconnected porosity, and forming a crust of material on the surface that came into contact with the power source. The lack of voids, pores, and associated porosity, along with the lack of downdraught suction of the gases, hindered the process until it reached the bottom of the crucible. Under these circumstances, the agglomerated material only went down to a depth of 12 to 15 mm, and at the end of the operation, the material was still unreacted beneath this crust. The high amount of wüstite in the finished product can be explained by the lack of porosity (especially interconnected porosity) and the inability of gases and air to circulate through the load, which prevented the oxidation of the wüstite created throughout the process [11–15]. One potent energy source is concentrated sun radiation. To accomplish the partial melting of the charge rather than the complete melting, better power management would be required. To simulate the industrial sintering process, we should additionally use the downdraught system to let the gases move through the load. It goes without saying that lower power levels are needed to prevent the load from melting completely. If we truly want to lower CO₂ emissions, we should also remove coke from the mixtures that are to be sintered. If we do this, the power of solar energy would only be used to initialize the mixture, and the emissions would only be somewhat reduced. In this manner, the agglomeration—rather than just the initializing system—should receive its heat from solar radiation.

Additionally, samples were examined using an electronic microscope, which allowed for point analysis to be done. A representative picture of the sun sintered samples is depicted in Figure 3, where the calcium and aluminum silico-ferrites are represented by Point 2 (matrix constituent) and the iron rich phase by Point 1 (disperse constituent).

RESULTS AND DISCUSSION

This set of studies yielded five samples in total. To determine the phases that were acquired during the tests, four samples were evaluated using the X-ray diffraction technique (conditions were given in the second section); Figures 4–7 show the results. Because of the experimental conditions (less than 5 minutes at the radiation level used in other tests, and incomparable findings), sample BF4 was not studied.

The chemical makeup of the crystalline phases of the samples when the amorphous phase is excluded. The crystalline phases were quantitatively analyzed using X Powder12 Ver. 01.02 software. Since the remaining material did not react during the trials, samples for X-ray diffraction studies were collected from the reacted compartment (12–20 mm in depth and 20–25 mm in diameter).

Potential Benefits of Solar Energy: Lower CO₂ Emissions and Expenses

In recent decades, several techniques based on the direct reduction of the ferric load have been investigated as alternatives to the blast furnace method of producing steel (smelting reduction). Some of these techniques, such as the direct reduction of hematite to produce magnetite in a fluidized bed solar furnace, rely on smelting reduction, as this paper illustrates, while others rely on direct reduction with gas. Approximately 72% of steel is now manufactured via the blast furnace and converter approach, despite the large variety of alternative techniques. The smelting reduction process, which is the basis of the procedure discussed in this paper, uses concentrated solar energy to provide heat to the operation and coke as a reductant. Since this publication presents basic research, more work should be done to scale up the process to an industrial level. However, in the lines that follow, we will outline the procedure's initial needs as well as the possible benefits of the solar method when compared to the conventional way [16–19].

To make one ton of steel, about 450 kilos of carbon (coke and pulverized coal) are needed. This carbon has three functions in the blast furnace, as the text previously stated: To keep the metal and slag in the lowest section of the furnace molten and to promote the reactions, 30% to 45% of the carbon is used to generate heat; 40% to 60% of the carbon is used to reduce the iron ore (the Ten to fifteen percent of the carbon is utilized to support the load in a reductant atmosphere).

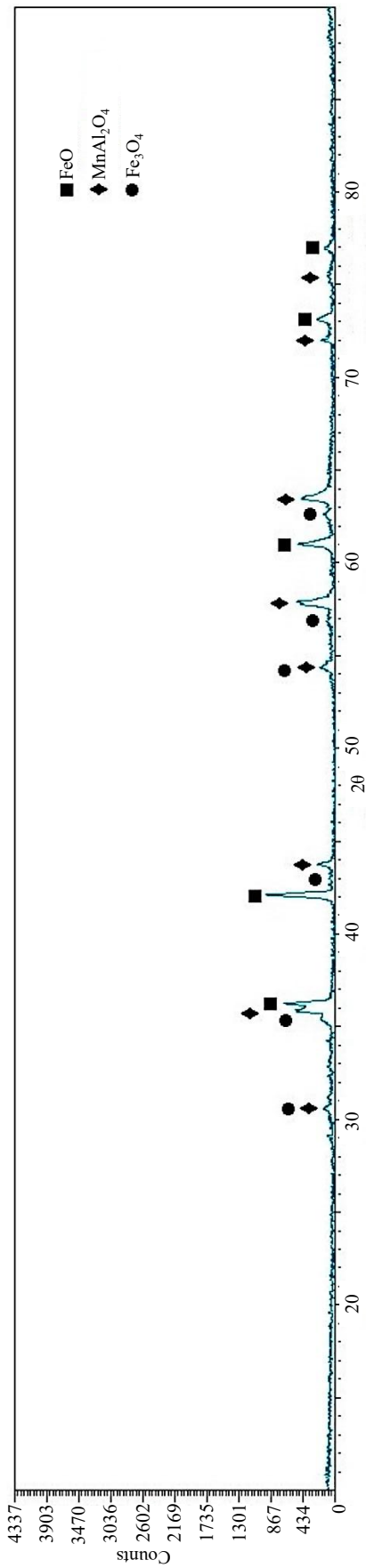


Figure 3. X-ray diffraction pattern of the sample Sint5.

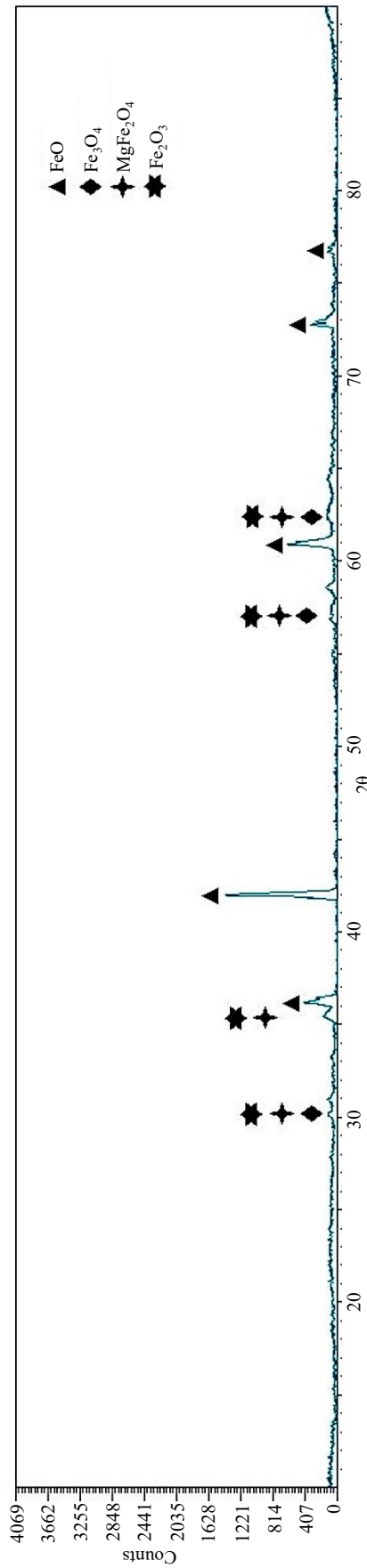


Figure 4. X-ray diffraction pattern for the sample BF1.

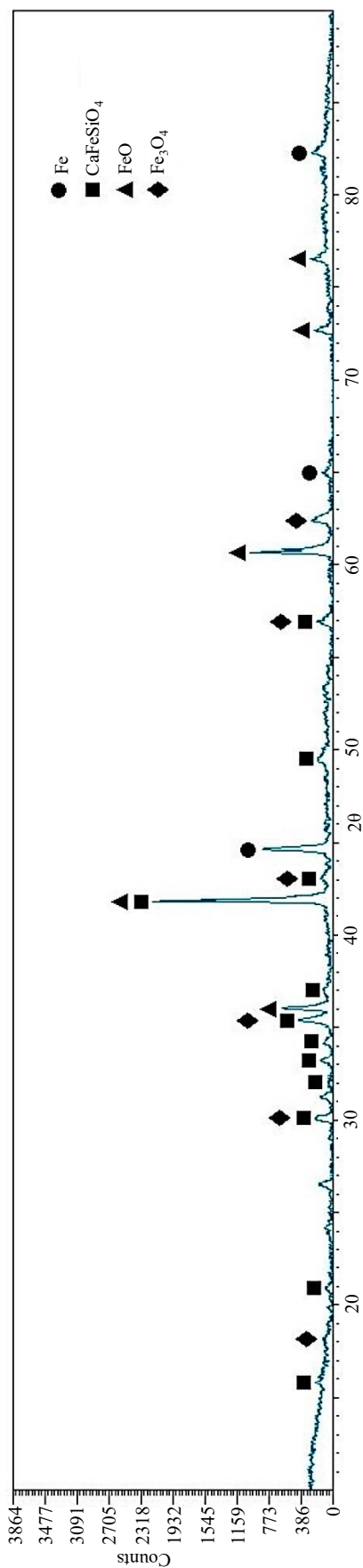


Figure 5. X-ray diffraction pattern for the sample BF2.

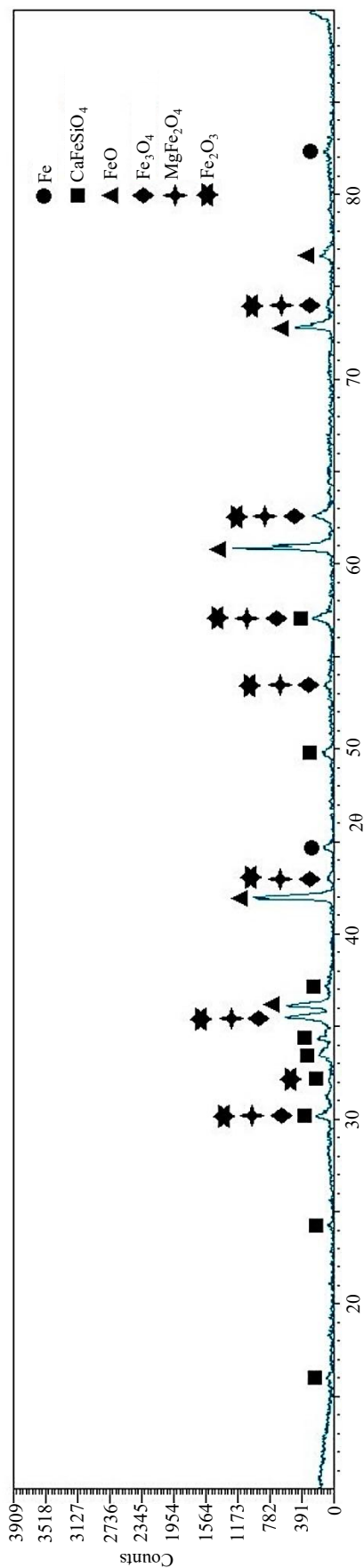


Figure 6. X-ray diffraction pattern for the sample BF3.

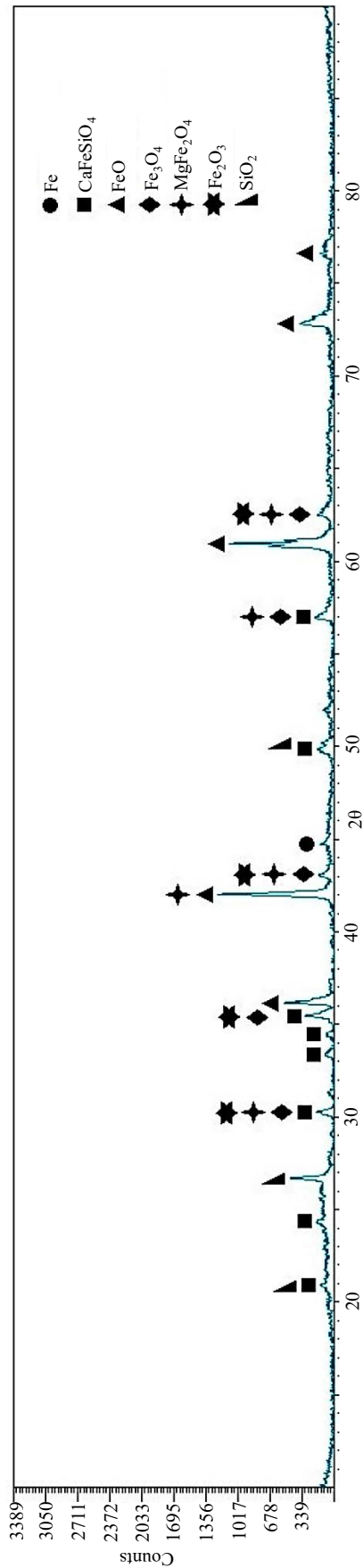


Figure 7. X-ray diffraction pattern for the sample BF5.

The coke needs to have the right porosity for gas circulation and be able to sustain the load at high temperatures. The Boudouard process states that the CO₂ and coke combine to form CO, which lessens the weight. This indicates that just 180 to 270 kg of coke are needed to manufacture 1 ton of steel and lessen the burden. Coke was only used to lessen the load in the procedure outlined in this paper; concentrated solar energy was employed to produce the heat; the costs of this energy would only be the installation and amortization expenses [20–25]. In the solar-based process, the cost of coke would be between 36 and 68 €/ton of steel (90–113 €/ton of steel via the BF and converter route), with a potential cost reduction of 45 to 54 €/ton of steel. This is because only 180 to 270 kg of coke would be required to produce 1 ton of steel, compared to the current price of 200 to 250 €/ton of coke. The reduction of CO₂ emissions might be calculated similarly (the BF and converter route produces about 1.5 to 1.8 tons of CO₂/ton of steel). However, the concentrated solar energy process could lower CO₂ emissions to 660 to 990 kg of CO₂/ton steel, since carbon and coke are only utilized to lower the load. This implies that CO₂ emissions could be cut by roughly 40% to 50%, which would benefit the environment and lower production costs because CO₂ emission taxes would be greatly lowered. The cost of emitting CO₂ is estimated by Trading System to be 22.5 €/ton CO₂ with an increasing trend. The possible reduction in CO₂ and coke usage (and hence price) may warrant greater research and application of concentrated solar energy in ironmaking, even if more work is required to scale up the process [26–30].

In order to operate in a closed environment (avoid oxidizing the air environment) or to stop the produced iron from reoxidizing in the presence of ambient atmosphere, a reductant atmosphere (CO or CO₂) is typically required for the installation of the solar furnace. In addition to reducing the load during smelting, the temperatures were high enough (>1500°C) to separate the metal from the slag. A continuous system passing beneath the focal point could solve the treated depth problem, but more potent solar furnaces could handle larger volumes of material (later, we indicate the solar processes developed to a demonstration scale, where they indicate quantities of tons daily could be produced). Numerous processes were investigated using concentrated sun energy, however not a single solar process related to materials was brought to industrial scale [31–35]. Thus, only two procedures were investigated for scaling up to the industrial level: using solar energy to store energy in the ZnO/Zn pair and producing lime in a solar furnace. Since the cost of solar lime would be double that of conventional lime, Meier et al. [33] constructed a kiln furnace that would be indirectly heated by a system of rotatory tubes. They concluded that this process may be used to produce lime of superior grade. In order to produce zinc (which can be used in water splitting to produce H₂ or as a combustible in batteries and combustible cells), it is now feasible to build (EU-SOL-ZINC, 0.3 MW solar plants for the production of 50 kg Zn/h) and design several demonstration plants (e.g., a 5 MW conceptual design of demonstration plant, 1700 kg Zn/h; and another of 30 MW to produce 10,000 kg Zn/h). These two lines of research give us the idea that, with careful study, concentrated solar energy could be used to produce steel (since large amounts of steel could be produced daily). This process could be applied in nations with a lot of solar energy because it would be less expensive and have less of an impact on the environment (as shown). Research on the use of concentrated solar energy in ironmaking may be justified by the possible decrease in CO₂ emissions, coke usage, and expenses [36–38].

CONCLUSIONS

When used effectively, concentrated solar energy has the potential to be used in thermal applications that might drastically lower carbon dioxide emissions. Iron ore agglomeration and iron oxide reduction are two important industrial processes that are the subject of this study's investigation into its use in ironmaking. Iron ore agglomeration: coke breeze and industrial iron ore combinations were used in the experiments. CO₂ emissions could be decreased by using solar energy to replace the coke used in the sintering process. The results, however, revealed serious difficulties. Reactions at depths of 12 to 15 mm were impeded by the melting of the upper surface caused by the high temperatures. Furthermore, the lack of a draught system impeded gas flow, which slowed down the process and led to significant amounts of wüstite because of insufficient oxidation. Although solar energy has the potential to replace coke as a heat source, its use in uniform sintering is limited by its punctual character.

Reduction of iron oxides: The study showed that replacing coke's heat source with solar energy might potentially lower CO₂ emissions using laboratory-grade iron oxide (III), carbon, industrial iron ore sinter, and coke breeze. However, since coke is necessary for the reduction process, its total eradication is still impossible. Magnetite, wüstite, and metallic iron were found in samples, indicating partial reduction. Because carbon monoxide escaped without lowering the charge, the air environment decreased the process's efficiency. Results could be enhanced by optimizing layer configurations (sinter above, coke below) and using a reductant or CO₂ environment. The potential of concentrated solar energy in metallurgical processes—specifically, the reduction of iron oxides—is demonstrated by this study. However, without more innovation, the use in iron ore agglomeration and wider industrial utilization is limited. For solar energy to become a competitive alternative to traditional methods in ironmaking, more study and technological developments are required.

Conflicts of Interest

The author declares no conflict of interest.

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