

Steel Plant Electrification: A Pathway to Sustainable Production and Carbon Reduction

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ABSTRACT

Traditional steel processes are energy-intensive and rely heavily on fossil fuels, contributing to significant greenhouse gas emissions. By adopting electrification technologies, such as electric boilers and compressors, particularly when powered by renewable energy, steel plants can reduce their carbon footprint, enhance process flexibility, and lower long-term operational costs. This transition also aligns with increasing regulatory pressures and market demand for greener practices, positioning companies for a more competitive and sustainable future. This work investigates the potential of replacing conventional steam crackers in a steel plant that relies on the use of fossil fuels, with electrically driven heating systems powered by renewable energy sources. The overall aim was to significantly lower greenhouse gas emissions by integrating electric furnaces and heat pumps into the steel production process. This study evaluates the potential carbon savings from the integration of solar energy in a steel plant with a production capacity of 300,000 tons per month. The solar field required for this integration was found to span an area ranging from 122,142 to 362,360 m², while the wind field area required is estimated at 550.373 m². By incorporating solar power into the plant's energy mix, the analysis reveals a significant reduction in carbon emissions, with an estimated saving of 707,597 tons of CO₂ per year.

Keywords: Electrification, Steel, Carbon Reduction, Optimization, GHG, additional keywords separated by commas

INTRODUCTION

The steel industry is among the most energy-intensive sectors globally, with traditional processes heavily dependent on fossil fuels. This reliance not only drives significant greenhouse gas (GHG) emissions but also poses challenges in meeting evolving environmental regulations and market expectations for sustainability. With the increasing availability of renewable energy and advancements in electrification technologies, steel plants have a transformative opportunity to decarbonize their operations.

Electrification of key processes, such as heating systems, using technologies like electric boilers, compressors, and heat pumps, offers a pathway to significantly reduce carbon emissions. These systems,

when powered by renewable energy, not only lower the carbon footprint but also enhance process efficiency and flexibility, positioning companies for long-term economic and environmental sustainability. Furthermore, transitioning to electric systems aligns with the growing demand for greener practices. Wei, McMillan and de la Rue du Can [1] reviewed the latest research on the potential for industry electrification to support decarbonization efforts. Sun, Wang [2] analysed carbon emission reduction strategies in the industry through the interconnection of carbon, electricity, and hydrogen, highlighting potential development directions. Hadera, Harjunkski [3] developed a continuous-time scheduling model to incorporate energy-awareness, optimizing electricity purchases and load commitments. Luh, Budinis [4] used a global energy system simulation to assess the impacts of CO₂ reduction measures, including fuel

switching, electrification, and Carbon Capture and Storage (CCS), on investment and operations. Several scenarios that evaluate the role of CO₂ pricing as a policy tool for decarbonizing the industrial sector were presented. Sun, Harjunkoski and Castro [5] used the Resource Task Network (RTN) examined the effect of fluctuating electricity prices on production scheduling the economic benefits of the steel plant's participation in incentive-based demand-side management (iDSM) programs. This study explores the feasibility of replacing conventional fossil-fuel-based steam crackers in steel production with electrically driven heating systems powered by renewable energy. The focus is on integrating electric furnaces and heat pumps into the steelmaking process to achieve substantial reductions in greenhouse gas emissions.

METHODOLOGY

Electrification offers a promising pathway to reduce carbon footprints by replacing fossil-fuel-based technologies with electric-driven alternatives powered by renewable energy sources such as wind, solar, or hydroelectric power. This paper explores the integration of electrification technologies, including electric furnaces, heat pumps, and renewable energy systems, like solar PV, wind, or CSP, into the steel production process. **(Figure 1)** By optimizing energy consumption and incorporating sustainable power sources, the methodology aims to significantly reduce greenhouse gas emissions and enhance operational efficiency. A critical aspect includes evaluating the feasibility of these technologies, assessing their environmental benefits, and performing cost analyses to ensure economic viability

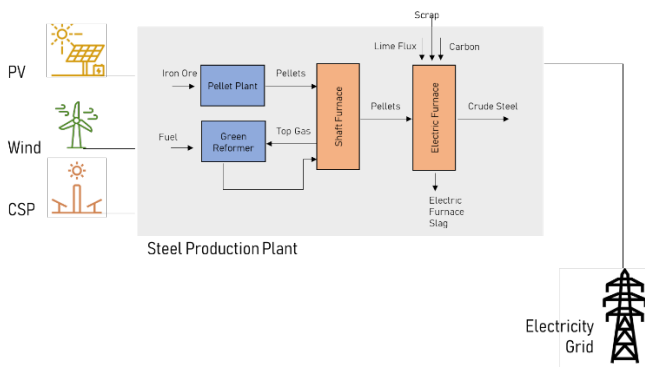


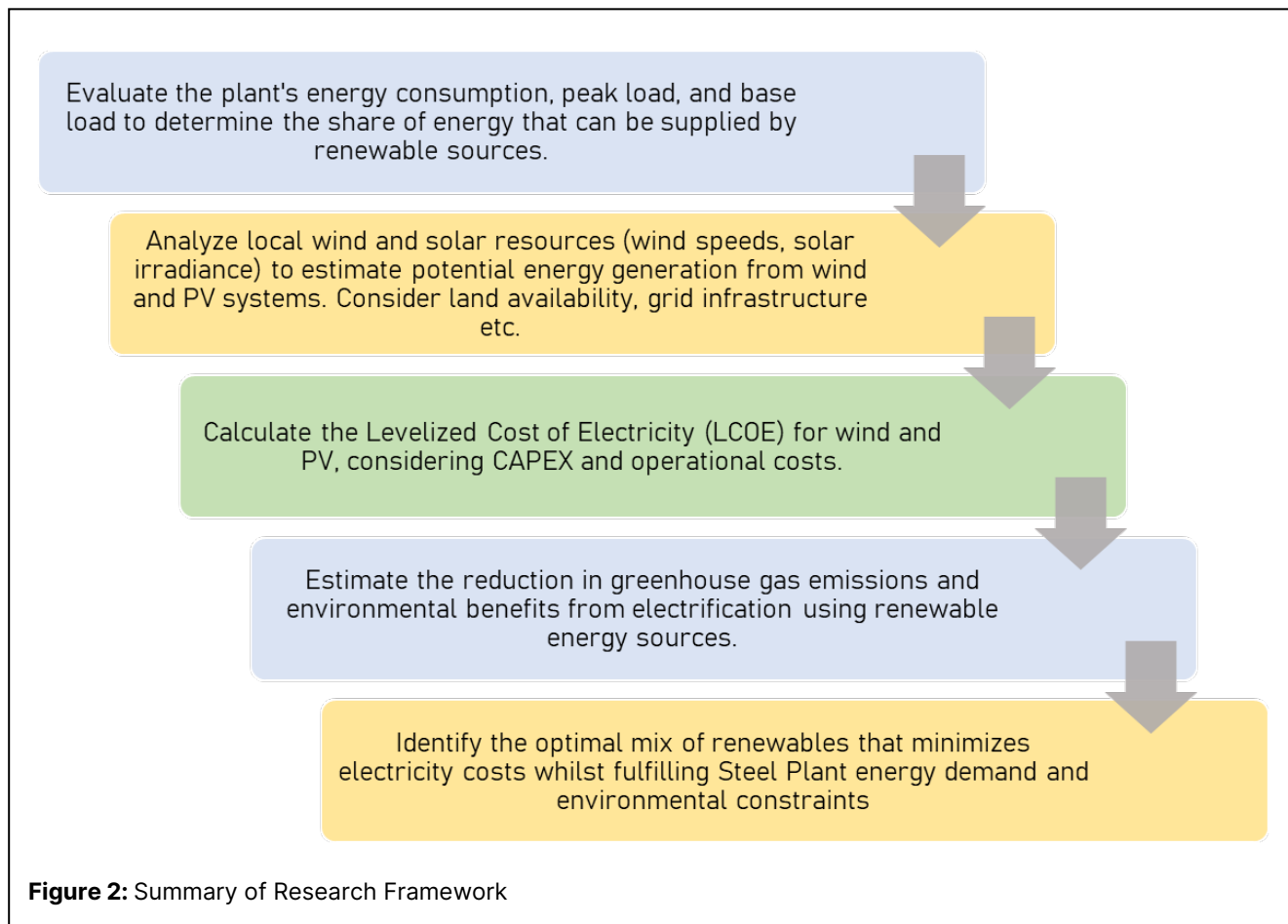
Figure 1. The integration of solar PV, wind, and CSP, into steel production

In this paper, a comprehensive approach to assessing the electrification options for a steel plant was made. **Figure 2** below summarizes the approach that was utilized in this work. First, the plant's current energy demand, including the total consumption, peak load, and

base load, was evaluated to identify how much can be replaced by renewable sources. This was then followed by an analysis of local renewable energy resources, such as wind and solar, based on site-specific conditions like wind speeds and solar irradiance, to estimate the potential energy generation from wind and photovoltaic (PV) systems. The feasibility of integrating these renewable sources into the plant's electrical system is then assessed, considering factors like land availability, grid connectivity, and required infrastructure upgrades. Economic modeling was then conducted by calculating the Levelized Cost of Electricity (LCOE) for both wind and PV technologies, factoring in CAPEX and OPEX expenditures. Additionally, the environmental impact of the steel plant was then evaluated after electrification options were introduced, focusing on the reduction of greenhouse gas emissions through the adoption of renewable energy. Finally, the most cost-effective and sustainable mix of wind and PV systems that supply the plant's energy needs while meeting the environmental constraints was identified.

CASE STUDY INFORMATION

The steel plant that was considered in this case study is a high-capacity facility with significant energy demands. The plant's operations require 186.264 MW of electrical power for various industrial processes, including smelting, rolling, and ancillary systems, which rely on a continuous and stable electricity supply. Additionally, the plant consumes 522.5 tons per hour of low-pressure (LP) steam at 3 bars, utilized for processes such as heating, drying, and maintaining operational conditions in different stages of steel production. To meet these intensive energy requirements sustainably, the proposed energy alternatives come from renewable energy sources, including solar PV, wind, and CSP, alongside advanced energy storage and conversion technologies. A lead-acid battery storage system is included to buffer the variability inherent in renewable energy generation, providing grid stability and ensuring uninterrupted power delivery during periods of low generation [6]. This is very important for processes that demand consistent power, as fluctuations can disrupt operations and reduce efficiency. Moreover, in order to meet the plant's steam requirements, electric boilers are incorporated to convert any surplus electricity into thermal energy, hence producing the required low-pressure steam for the plant's operation.



RESULTS AND DISCUSSION

The results of the study are summarized in **Table 1**, which highlights the differences in land use, energy cost, and CO₂ savings for each renewable energy option

Table 1: Summary of Parameters associated with CSP, PV and wind energy

Parameter	CSP	PV	Wind
Land Area (m ²)	122,142	362,360	550,373
No. Panels /Turbines	-	181,180	272
Cost (USD/kWh)	0.165	0.096	0.055
CO ₂ Savings (tons/y)	629,868	569,413	675,930

CSP systems use solar thermal technology to generate electricity and heat, making them an ideal candidate for dual production of electricity and steam. In this study, CSP requires a land area of 122,142 m² to meet the plant's energy demands. Although CSP inherently supports thermal energy storage, the integration of Pb-acid

batteries ensures continuous operation during periods of low solar irradiance. The levelized cost of energy (LCOE) for CSP was calculated at \$0.165/kWh, the highest among the technologies evaluated. PV systems are assessed for their cost-effectiveness and scalability. Covering an area of 362,360 m², the PV system includes 181,180 panels to generate the required power. Since PV systems produce only electricity, electric boilers are incorporated to fulfill the steam demand. The LCOE for PV is \$0.096/kWh with storage and \$0.049/kWh without storage, showcasing its competitive advantage. However, the dependency on battery storage for consistent operation poses challenges related to cost and efficiency. Wind turbines were evaluated at an average wind speed of 7 m/s. To meet the plant's energy requirements, 272 turbines occupying 550,373 m² were proposed. With an LCOE of \$0.055/kWh, wind energy proves to be the most economical option with storage. The cost drops further to \$0.032/kWh when storage is excluded. Interestingly, if wind speeds increase to 9 m/s, the LCOE reduces to \$0.047/kWh, demonstrating the high sensitivity of wind energy costs to wind conditions. Despite the variance in cost and land area, the CO₂ emissions reduction from operation is identical across the three technologies and estimated at 707,597 tons/y. This uniformity arises

from the complete replacement of natural gas with renewable sources. However, when considering the CO₂ life cycle assessment (LCA) of each technology, the actual net emissions reduction differs due to the embedded emissions in manufacturing, transportation, installation, maintenance, and decommissioning. CSP, with a lifecycle emission factor of 27 g CO₂/kWh, achieves a reduction of 629,868 tons/year. PV, having a higher emission factor of 48 g CO₂/kWh, results in a slightly lower reduction of 569,413 tons/year. On the other hand, wind energy, with the lowest lifecycle emissions at 11 g CO₂/kWh, leads to the highest reduction of 675,930 tons/year [7]. These results highlight the importance of considering full life cycle emissions when assessing the environmental impact of renewable technologies. While all three sources significantly reduce emissions compared to fossil fuels, wind energy emerges as the most effective in minimizing CO₂ footprint, followed by CSP and then PV.

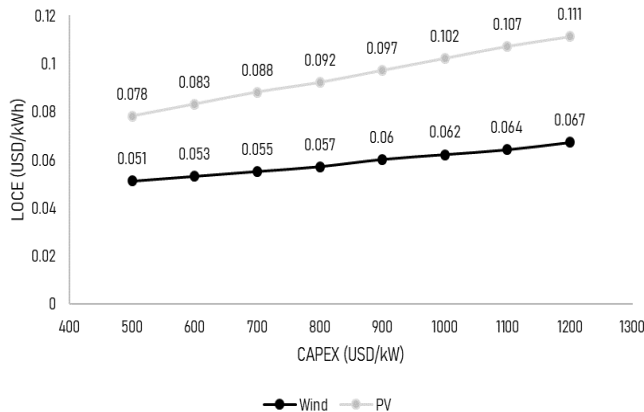


Figure 3. Optimal costs attained for Steel Electrification via PV and Wind technologies

The use of electric boilers is a pivotal adaptation for PV and wind systems, as these technologies generate electricity exclusively. This ensures that the steel plant's LP steam requirements are met without compromising its operational integrity. The integration of Pb-acid batteries across all systems addresses intermittency issues, though the added cost impacts overall feasibility. From an economic standpoint, wind energy emerges as the most viable option, particularly in regions with high average wind speeds. The reduced LCOE at higher wind speeds further enhances its competitiveness. However, the extensive land requirement for wind turbines and PV systems poses logistical challenges, especially in densely populated or land-constrained areas. CSP, while requiring less land, is the most expensive option and may be less attractive unless thermal energy storage provides significant operational advantages. Further studies could explore alternative storage technologies, such as lithium-ion batteries, which may offer improved efficiency and lower costs. Additionally, hybrid solutions that combine

CSP with PV or wind could optimize resource utilization and mitigate individual technology limitations.

A sensitivity analysis was performed to assess the impact of the capital expenditure on the levelized cost. **Figure 3** shows the results that were attained for wind and PV energy systems. The results indicate that as CAPEX increases from 500 to 1200 units, the LCOE for both wind and PV systems also increases. For wind, the LCOE increases from 0.051 to 0.067 USD/kWh, while for PV, it increases from 0.078 to 0.111 USD/kWh.

It is evident that PV systems have a higher LCOE compared to wind systems at all CAPEX levels, reflecting higher costs for generating electricity from PV systems under these conditions. The rate of increase in LCOE appears consistent for both technologies, suggesting a proportional relationship between CAPEX and operational costs. Moreover, while wind energy appears more cost-effective for the steel plant in this case study, regional factors such as resource availability, land use, and grid infrastructure can influence the decision-making process.

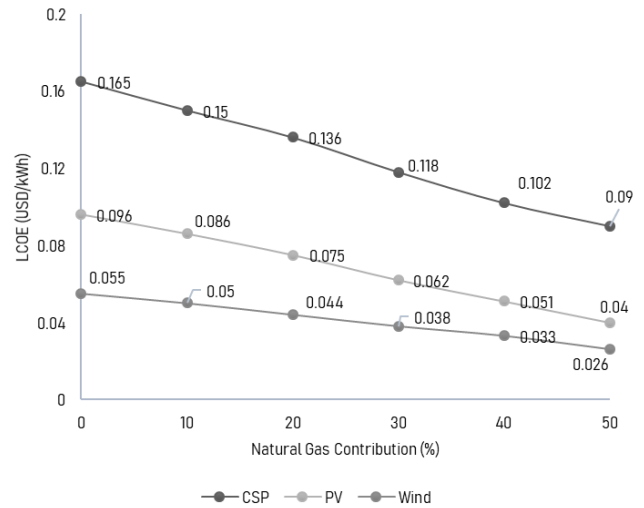


Figure 4. Natural gas (NG) price sensitivity on the levelized cost of electricity (LCOE) for CSP, PV and wind

Figure 4 demonstrates the sensitivity analysis conducted on the effect of natural gas (NG) contribution on the levelized cost of electricity (LCOE) for CSP, PV, and wind technologies. A clear trend is observed; increasing the share of NG in the energy mix leads to a reduction in LCOE across all three renewable technologies. This trend is expected since NG is typically a lower-cost generation source compared to renewable technologies, especially when considering the high capital expenditure (CAPEX) of CSP and PV systems.

At 0% NG contribution (i.e., fully renewable operation), CSP exhibits the highest LCOE (0.165 \$/kWh), followed by PV (0.096 \$/kWh), and wind (0.055 \$/kWh). As NG contribution increases to 50%, the LCOE for all

technologies decreases significantly, reaching 0.09 \$/kWh for CSP, 0.04 \$/kWh for PV, and 0.026 \$/kWh for wind. This reduction can be attributed to the lower cost of NG electricity production and the reduced reliance on high-capital-cost renewable infrastructure. Among the three technologies, CSP experiences the most significant absolute decrease in LCOE (from 0.165 \$/kWh to 0.09 \$/kWh), reflecting its higher initial cost and greater sensitivity to hybridization with conventional power sources. On the other hand, wind, which starts with the lowest LCOE, exhibits the least reduction, dropping from 0.055 \$/kWh to 0.026 \$/kWh, indicating that its cost structure is already competitive with NG.

These findings highlight the economic advantage of incorporating a certain percentage of NG into renewable energy systems to reduce costs. However, the trade-off between cost reduction and carbon emissions should be carefully considered when optimizing the energy mix for sustainability goals.

CONCLUSIONS

The adoption of electrification technologies, particularly when combined with renewable energy sources, offers a promising pathway for decarbonizing the energy-intensive steel industry. This study demonstrates the potential of replacing conventional fossil-fuel-based steam crackers with electrically driven heating systems, such as electric furnaces and heat pumps, powered by solar or wind energy. The integration of wind and solar power into the steel plant's energy mix resulted in a substantial reduction in carbon emissions, with an estimated annual savings of 2,831 tons of CO₂. By integrating renewable energy sources like CSP, wind, or PV, steel plants can easily shift from fossil fuel dependence to cleaner electricity, reducing their environmental impact.

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