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Quantifying the Carbon Mitigation Potential of Waste Heat Recovery Systems (WHR) in Sponge Iron Plant: A study of Decarbonisation

Avantika Saha[1], Rashmi Mishra[2], Dr. Sapan Kumar Saha[3]

[1]Scholar, M.Tech. (Environment Engineering), Department of Chemical Engineering, RITEE, C.G., India.
[2]Scholar (Environment Science) & Chief Chemist, Environment, Municipal Corporation, Bilaspur, Chhattisgarh, India.
[3] BEE- Certified Energy Manager (NPC Govt. of India) & Chief Operating Officer, Hitech Power and Steel Limited, Raipur, Chhattisgarh, India

Abstract:
The iron and steel sector is a major contributor to global greenhouse gas (GHG) emissions, with coal-based Direct Reduced Iron (DRI) or sponge iron production exhibiting a severe carbon footprint. A critical inefficiency in conventional rotary kiln sponge iron plants is the rejection of 30% to 40% of thermal energy input via high-temperature flue gases (800°C–1000°C) directly into the atmosphere. This paper evaluates the thermodynamic feasibility and carbon mitigation potential of integrating Waste Heat Recovery (WHR) systems within the sponge iron industry under the governance of the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (CDM). The sponge iron industry, a vital component of the global steel supply chain, is highly energy-intensive and historically associated with a massive carbon footprint. As countries strive to meet stringent net-zero emission targets, industrial decarbonization has transitioned from an environmental ideal to a regulatory and economic necessity. Among the various technological interventions available, Waste Heat Recovery Systems (WHR) have emerged as one of the most commercially viable and impactful solutions for reducing greenhouse gas emissions in energy-heavy manufacturing.

Adhering to the approved consolidated baseline methodology ACM0012, this study models mass-and-energy balancing alongside carbon accounting equations to quantify the net reduction in carbon dioxide (CO_2) emissions achieved by displacing carbon-intensive grid electricity with clean, captive power generation. The findings indicate that WHR integration significantly decreases localized thermal pollution while providing a highly predictable volume of Certified Emission Reductions (CERs) to bolster project financial additionality. However, sensitivity analysis reveals that the long-term carbon mitigation value is heavily vulnerable to the progressive decarbonization of the regional power grid, which systematically reduces the baseline grid emission factor over time. By employing a combination of thermodynamic mass-and-energy balancing and carbon accounting methodologies, this study quantifies the potential reduction in (CO_2) emissions achievable through optimal waste heat integration. Using process-based mass and energy balance calculations from a standard 3x100 Tons per day (TPD)

rotary kiln plant, it is estimated, how much grid-purchased electricity can be replaced by recovered heat? This study reveals that WHRB based captive power plant, mitigates approximately 50934 tonnes of CO_2 per year by avoiding emissions from coal-fired grids. Ultimately, this research aims to provide policymakers and industry stakeholders with a data-driven framework to accelerate energy efficiency improvements and advance the circular economy within the iron and steel sector.

Keywords: Waste Heat Recovery (WHR), Sponge Iron Plant, Carbon Mitigation, Clean Development Mechanism (CDM), ACM0012, Energy Efficiency, Industrial Decarbonization.

1. Introduction

The iron and steel sector is one of the most energy-intensive and carbon-heavy industries globally. This sector is a dominant pillar of global industrial infrastructure, but it is also one of the largest contributors to global climate change, accounting for approximately 7% to 9% of direct anthropogenic carbon dioxide (CO_2) emissions. Within this sector, the coal-based Direct Reduced Iron (DRI) or sponge iron process plays a critical role, particularly in developing economies where local raw materials dictate production routes [1]. The production of Direct Reduced Iron (DRI) commonly known as sponge iron presents a severe carbon liability, particularly in developing economies where coal-based rotary kiln technology is widely utilized due to the abundance of non-coking coal. As nations tighten their nationally determined contributions (NDCs), transitioning the energy-intensive sponge iron industry toward low-carbon operations has evolved from an environmental ideal into an urgent regulatory necessity [2].

India is the world's leading producer of sponge iron. More than 80% of this production relies on coal-based rotary kilns rather than natural gas. Coal-based Direct Reduced Iron (DRI) production in rotary kilns is highly carbon-intensive. It releases substantial volumes of high-temperature off-gases into the atmosphere. In a conventional coal-based sponge iron plant, thermodynamic inefficiencies are pronounced. Roughly 30% to 40% of the total thermal energy input is rejected into the atmosphere as high-temperature flue gases, exiting the rotary kiln at temperatures ranging between 800°C and 1000°C. Discharging this high-enthalpy waste gas represents a massive waste of valuable energy and contributes heavily to local thermal pollution. Waste Heat Recovery (WHR) systems mitigate these inefficiencies by routing the flue gas through a Waste Heat Recovery Boiler (WHRB) to generate superheated steam, which is subsequently expanded in a steam turbine generator to produce clean, captive electricity [3] [4].

To bridge the gap between technological feasibility and financial viability, market-based environmental instruments are frequently deployed. Among these, the Clean Development Mechanism (CDM) provides a structured framework for quantifying and certifying emission reductions. By applying rigorous, approved baseline and monitoring methodologies specifically ACM0012 (Consolidated baseline methodology for GHG emission reductions from waste energy recovery projects) sponge iron plants can convert verified thermal efficiency gains into Certified Emission Reductions (CERs). This institutional mechanism provides the critical carbon financing needed to offset high upfront capital investments and alter the techno-economic viability of industrial energy efficiency projects [5] [6]. While the thermodynamic principles of industrial waste heat utilization are well-documented, a comprehensive synthesis integrating physical exergy destruction with the regulatory stringency of CDM accounting frameworks remains sparse in contemporary literature. The exact carbon mitigation potential depends heavily on highly localized dynamic variables, including the operating capacity of the rotary kilns, the grid emission factor of the host country's national grid, and the internal parasitic electrical loads of the WHR infrastructure itself. This study evaluates the carbon mitigation potential of WHR systems within the sponge iron industry under the strict governance of the CDM framework. By employing a dual approach combining thermodynamic mass-and-energy balancing with CDM-compliant baseline methodologies, it quantifies the absolute net CO_2 reductions and potential CER yields across standard operational capacities [7]. This study evaluates the carbon mitigation potential of implementing Waste Heat Recovery Systems (WHR) paired with Waste Heat Recovery Boilers (WHRB) to generate captive power.

The implementation of WHR systems primarily offsets the plant's reliance on fossil-fuel-dominated national grids or dedicated coal-fired captive power plants. Consequently, evaluating the decarbonization impact requires a rigorous understanding of the displacement grid emission factors, internal parasitic loads, and thermal recovery efficiencies under fluctuating kiln operating conditions. Integrating Waste Heat Recovery (WHR) systems specifically through Waste Heat Recovery Boilers (WHRB) coupled with steam or organic Rankine cycles presents a foundational pathway to bridge this efficiency gap. By tapping the thermal energy of the flue gas, a 350,000 MTPA plant can generate substantial captive electricity without consuming incremental fossil fuels, effectively displacing carbon-heavy power drawn from the national grid. This study addresses this gap by presenting a rigorous thermodynamic and environmental analysis [8] [9].

2. Literature review

The integration of Waste Heat Recovery (WHR) systems in heavy industries has long been recognized as a cornerstone of industrial energy efficiency and carbon management. Early literature heavily focused on the thermodynamic feasibility and exergy analysis of capturing high-temperature exhaust gas from energy-intensive sectors such as cement, glass, and iron manufacturing. In the context of the iron and steel industry, particularly coal-based Direct Reduced Iron (DRI) or sponge iron production, researchers have consistently highlighted that 30% to 40% of thermal energy input is rejected through flue gases at temperatures exceeding 800°C [10] [11].

Historically, the high capital expenditure required for installing Waste Heat Recovery Boilers (WHRBs) and steam turbine generators acted as a significant barrier to widespread adoption in developing nations. However, the introduction of market-based mechanisms under the Kyoto Protocol, specifically the Clean Development Mechanism (CMD), fundamentally altered the techno-economic landscape. The implementation of CDM allowed industrial project developers to monetize greenhouse gas (GHG) emission reductions into Certified Emission Reductions (CERs), effectively lowering the payback period of energy efficiency investments. Scholars examining CDM projects in heavy manufacturing have noted that the additionality criterion—proving that the project would not have occurred without carbon finance—is highly sensitive to regional energy costs and grid structures. In the sponge iron sector, waste energy recovery projects predominantly utilize the UNFCCC approved consolidated baseline methodology ACM0012 ("Consolidated baseline methodology for GHG emission reductions from waste energy recovery projects") [7] [12].

Literature evaluating ACM0012 applications reveals that the methodology provides a highly conservative yet transparent accounting framework. Previous studies assessing baseline grid replacements have demonstrated that the carbon mitigation impact of WHR is directly proportional to the carbon intensity of the displaced grid. For instance, in regions with coal-heavy grids (such as India or China), the displacement of grid electricity by captive WHR power yields a significantly higher emission reduction factor compared to regions reliant on renewable or nuclear-heavy grids. Despite the wealth of literature on generic waste heat utilization, contemporary research often separates the purely thermodynamic evaluation of sponge iron plants from the rigorous, regulatory math required by carbon accounting bodies. Fluctuations in kiln operational parameters, varying ash content in non-coking coal, and internal parasitic loads of the WHR plant itself introduce dynamic uncertainties. This paper bridges that gap by synthesizing industrial mass-and-energy balances with the strict mathematical boundaries defined by the CDM framework to project highly accurate carbon mitigation outcomes [13] [14].

A standard coal-based rotary kiln operates at temperatures between 1000ºC and 1100ºC. The process discharges off-gases at approximately 800ºC and 1000ºC. These gases carry massive amounts of unutilized sensible and chemical heat. Historically, this heat was wasted through stack dissipation after passing through an Electrostatic Precipitator (ESP). Installing a WHR system captures this thermal energy. It generates high-pressure steam for power production without consuming any additional fossil fuels. This article evaluates the net carbon reduction achieved by replacing grid-tied fossil fuel electricity with clean, recovered thermal energy [15].

"Waste Heat Recovery Systems (WHRS) in coal-based rotary kiln DRI plants can significantly reduce carbon footprints, with optimized systems achieving 20 to 30% emission reductions by capturing high-temperature flue gases. Studies emphasize that while emerging technologies like green hydrogen face high capital costs, WHR integration remains a highly viable immediate strategy for industrial sustainability and GHG abatement" [16] [17].

3. Methodology & mathematical framework

3.1 Objective of the study

➢ To estimate the annual greenhouse gas emissions avoided by implementing a Waste Heat Recovery (WHR) system in a Sponge Iron Plant.

3.2 Structure of the Study: This paper is structured as a system:

➢ **System Boundary Selection**: Establishes the specific data boundaries for the 350,000 MTPA plant facility.

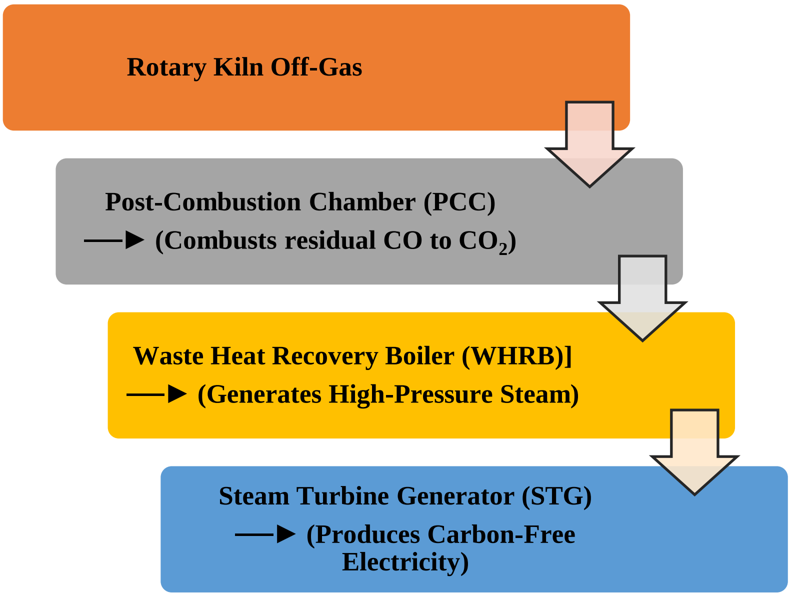
➢ **Understanding CDM methodology for emission reduction**

➢ **Thermodynamic Performance Evaluation**: Utilizes first and second-law energy balances to trace energy destruction (exergy) bottlenecks.

➢ **Carbon Mitigation Quantification**: Calculates net avoided (CO_2) emissions against regional grid baselines to define empirical environmental benchmarks for heavy industrial decarbonization [18].

3.2.1 System Boundary: The system boundary for this assessment spans from the kiln discharge off-gas stream through the Post-Combustion Chamber (PCC), the Waste Heat Recovery Boiler (WHRB), and the Steam Turbine Generator (STG).

Figure 1: The system boundary for this assessment of WHR potential



This study has been carried out at Hitech Power and steel Limited, Tilda, Raipur. Company is presently operating 3x100 TPD Songe Iron Kiln, 18 MW CPP (12 MW WHRB + 6 MW AFBC), Induction Furnace with CCM and Rolling Mill. The project is registered as HITECH CDM CPP in UNFCCC. For this study total CO_2 emission reduction for the period of 5 years have been quantified [19].

3.2.2 Understanding CDM methodology for emission reduction: The primary objective of this methodology is to quantify the net greenhouse gas (GHG) emission reductions achieved by substituting grid-connected or fossil-fuel-based captive power with clean electricity generated from a Waste Heat Recovery (WHR) system in a sponge iron plant. The estimation framework strictly adheres to the UNFCCC CDM Consolidated Methodology ACM0012 [20] [21] [22].

The net emission reduction (ER_y) achieved by the project activity during a given year (y) is computed as the difference between the baseline emissions (BE_y), the project emissions (PE_y), and any potential leakage emissions (LE_y):

$$\mathbf{ER_y = BE_y - PE_y - LE_y} \qquad (1)$$

Where:

- ER_y = Emission reductions in year y (tCO_2e\year)
- BE_y = Baseline emissions in year y (tCO_2e\year)
- PE_y = Project emissions in year y (tCO_2e\year)
- LE_y = Leakage emissions in year y (tCO_2e\year)

Determination of Baseline Emissions (BE_y): Under ACM0012, if the recovered waste heat is used to generate electricity that displaces electricity from the national grid, the baseline emissions are calculated based on the quantum of electricity generated multiplied by the baseline emission factor of the grid:

$$BE_y = EG_{PJ,y} \times EF_{grid,y} \quad (1.1)$$

Where:

- $EG_{PJ,y}$ = Net quantity of electricity generated by the WHR system and supplied to the plant, replacing grid electricity year y (tCO_2e\year)
- $EF_{grid,y}$ = CO2 emission factor of the grid in year y (tCO_2e\year)

The net electricity generated $EG_{PJ,y}$ is determined by subtracting the internal parasitic load ($EG_{parasitic,y}$) of the WHR system (cooling towers, boiler feed pumps, etc.) from the gross electricity generated by the steam turbine ($EG_{gross,y}$):

$$EG_{PJ,y} = EG_{gross,y} - EG_{parasitic,y} \quad (1.2)$$

Determination of Project Emissions: PE_y Project emissions account for any greenhouse gases emitted directly because of the project implementation. In a typical WHR configuration where no auxiliary fossil fuel is fired in the Waste Heat Recovery Boiler (WHRB) to supplement the steam generation, direct project emissions from fuel combustion are zero. However, if fossil fuel is used for startup or flame stabilization, or if additional electricity is consumed from an external fossil source to run the WHR plant that wasn't accounted for in the parasitic load deduction, it is calculated as:

$$PEy = PE_{comb,y} + PE_{elec,y} \quad (1.3)$$

For a standard, strictly waste-gas-driven WHR system: $PE_y = 0$.

Leakage (LE_y): According to ACM0012, leakage emissions (LE_y) due to the transfer of equipment or adjustments outside the project boundary are generally considered negligible for this specific type of technology, provided no energy-recovery equipment is being diverted from another pre-existing baseline facility. Hence: $LE_y = 0$.

3.2.3 Thermodynamic Estimation of Power Potential

Thermodynamic Evaluation of Waste Heat Availability To link the CDM equations to the physical plant dynamics, the maximum potential steam generation is modeled through a thermal energy balance of the flue gas leaving the rotary kiln. The thermal energy available in the flue gas can be computed using the following equation [23] [24] [25] :

$$Q = m \cdot C_p \cdot \Delta T \quad (2)$$

Where:

Q	=	Thermal energy available (kW);
m	=	Mass flow rate of the off-gas (kg/s);
C_p	=	Specific heat capacity of the flue gas (kJ/kg °C);
ΔT	=	Temperature drops across the boiler ($T_{inlet} - T_{outlet}$).

According the process department of Hitech Power and Steel Limited, the for ideal 100 TPD DRI Sponge Iron Kiln at the off-gas generation rate is disclosed roughly 21.6 t/h or 6kg/s at an inlet temperature of 950ºC. Assuming a boiler outlet temperature of 180ºC to prevent acid dew point corrosion, T = 770ºC. Mass Flow rate calculation (Unit conversion) is done as below:

$$m = \frac{21.6\ tonnes}{hour} \times \frac{1000\ kg}{1\ tonne} \times \frac{1\ hour}{3600\ seconds} = 6.0 kg/s$$

Available thermal Energy: Substituting the mass flow rate (m = 6.0 kg/s) and the updated temperature drop (Δ T, with T = 870 ºC) into the thermodynamic equation:

$$\mathbf{Q\ =\ m.Cp.\Delta\ T}$$

$$Q = \frac{6.0kg}{s} \times C_p \left(\frac{kJ}{kg°C}\right) \times 870°C$$

$$Q = 5220 \cdot C_p\ kW$$

	Assuming C_p = Specific heat capacity of the flue gas (kJ/kg ºC)	Q = Thermal energy available (kW)
Scenario A	1.10	5742
Scenario A	1.15	6003
Scenario A	1.20	6264

Baseline Industrial Scenarios: Depending on the exact composition of the flue gas from your sponge iron rotary kiln, the typical specific heat capacity (C_p) ranges between **(1.10)** and **(1.20 kJ/kg ºC)** at these elevated temperature levels. The heat equivalent of 1 Megawatt-hour (MWh) is exactly 3.412 million British Thermal Units (MMBtu) or 3.6 Gigajoules (GJ). Because 1 MWh equals 3.6×10^9 Joules, it is a universal measure of energy that can be converted directly into heat.

3.2.4 Baseline calculation for HITECH CDM CPP: calculation of coal based captive power plant efficiency could be understood by considering an example of 10 MW WHRB based captive power generation, in accordance with the CMD protocol, as given in Table 1 below:

Table 1: Power generation efficiency calculation

Parameter	Description	Value	Unit
Power Output	Target generation capacity	10	MWh
Total Steam Flow	Steam requirement for 10 MWh	42,930	kgs/hr
S1	Steam required per **1 MWh**	4,293	kgs/MWh
E1	Conservative Steam Enthalpy (at 6.4 MPa, 490°C)	3,393.8	kJ/kg
Enthalpy per MWh	Enthalpy added per MWh (S1 x E1)	14,569,583.4	kJ/MWh
E2	Total energy added in TJ	**0.014569583**	TJ/MWh
H1	Heat equivalent of 1 MWh (3.6×10^9) Joules)	**0.0036**	TJ/MWh
ηBoiler	Assumed Boiler Efficiency	100	%
Eff $_{Captive, y}$	Final Captive Power Generation Efficiency (H1 /	**24.709011%**	%

	E2)		

(Data source: UNFCC, HITECH CDM CPP 1693 [26])

Considering the boiler efficiency as 100%, that is Heat Generated by Coal NCV goes to provide Steam Enthalpy. The Efficiency of Captive Power Generation (EF Captive, y) is calculated by dividing the Heat equivalent of 1 MWh by Enthalpy added per MWh power Generation (H1/ E2) it comes around 24.709011%.

Eff $_{\text{Captive}}$, y = 24.709011%

Selecting more conservative parameters gives highest captive power efficiency.

3.3 **Calculation of emission factor for captive power baseline**: the formula used for this purpose is as below

$$EF\ captive, y = \frac{EF\ CO^2, I}{Eff\ captive} \times \frac{44}{12} \times \frac{3.6}{1000} \quad (3)$$

$source: UNFCCC\ HITECH\ CDM\ PDD$ [26]

Where,

- EF captive, y = Emission factor for captive power generation (t CO_2/MWh)
- EF CO_2,i = CO_2 emission factor of fuel used in Captive Power Generation t C/TJ to be conservative.
- Eff captive = Efficiency of Captive Power Generation (%)
- $\frac{44}{12}$ = Carbon to Carbon Dioxide conversion factor.
- $\frac{3.6}{100}$ =TJ to MWh conversion factor.

Emission factor calculation is shown in table 2:

Table 2: Emission factor calculation

Parameter	Operational/Methodological Metric	Value	Unit
$\eta_{captive}$	Captive Power Generation Efficiency	**24.709011**	%
EF $_{CO2,i}$	IPCC Carbon Emission Factor (Coking Coal)	**26.20**	tC/TJ
C → CO_2	Molecular Oxidation Factor (44/12)	**3.666666667**	Ratio
Constant	Energy Metric Multiplier (3.6/1,000)	**0.0036**	TJ/MWh
EF$_{captive, y}$	**Final Baseline Emission Factor**	**1.399651312**	tCO_2e/MWh
Emission Factor 1.39 tCO_2eq /MWh			

(Data $source: UNFCCC\ HITECH\ CDM\ CPP;\ PDD$ [26])

3.4 Carbon Mitigation Accounting: The baseline emission reduction (ER_y) achieved by the WHR power plant is calculated using Clean Development Mechanism (CDM) methodologies [21] [22] :

$ER_y = EG_y \cdot EF_{grid}$

Where:

- ER_y = Net emission reductions in year (tCO_2e/year)
- EG_y = Net electricity generated and consumed from WHR (MWh/year)

- EF_{grid} = Combined margin CO_2 emission factor of the grid (tCO_2/MWh)

4. Results and empirical analysis

Based on industry operational configurations, the performance metrics for the power generation from AFBC and WHRB has been taken for the period of 5 years. For the authentication data of the FY 2021-22 has been disclosed in the table 3 below. In developing nation like India other CDM entities have also validate comparable outcomes [27] [28].

Table 3: Snapshot of power generation (2021-22)

- Month	**POWER GENERATION BOILER WISE (KWH)**					**POWER GENERATION FROM WHRB (MWH)**			
	AFBC	**WHRB-1**	**WHRB-2**	**Total Generation**	Auxiliary Consumption	**Power generation from WHRB**	**% of power generation from WHRB**	**Auxiliary Consumption from WHRB generation**	**Net generation**
	A	**B**	**C**	**D (A+B+C)**		**B+C**			
Apr-21	4837656	1315117	1262528	7415301	839150	2577645	35	291698	2285947
May-21	4031581	1740061	1816956	7588598	860650	3557017	47	403414	3153603
Jun-21	4384759	1078781	1075460	6539000	786280	2154241	33	259036	1895205
Jul-21	4166316	1788993	1747192	7702501	889960	3536185	46	408577	3127608
Aug-21	4806489	1309632	1732682	7848803	907210	3042314	39	351648	2690666
Sep-21	4560728	1716386	1274182	7551296	1379950	2990568	40	546507	2444061
Oct-21	4968189	1393820	1422893	7784902	841970	2816713	36	304639	2512074
Nov-21	4191272	1922499	1749634	7863405	809720	3672133	47	378131	3294002
Dec-21	5003770	1502715	1486514	7992999	810520	2989229	37	303119	2686110
Jan-22	3918502	1574129	1625968	7118599	742490	3200097	45	333779	2866318
Feb-22	3562059	1404049	1470089	6436197	638630	2874138	45	285186	2588952

Mar-22	4881899	1170153	1338947	7390999	837750	2509100	34	284400	2224700
TOTAL	53313220	17916335	18003045	89232600	10344280	**35919380**		4150134	**31769246**

(AFBC- Air Fluidized Bed Combustion) uses fossil fuels.

Year	Capacity (in MW)	Operational days per year	operational hours per day	Gross generation in MWH	Auxiliary consumption	Net generation in MWH	Emission Factor tCO2eq/MWh	Net CO2 reduction achieved tCO2eq
2021-22	4.5	350	24	35919	4150	31769	1.390	44159

Table 4: Estimation of CO_2 reduction in 5 years (2021-22 to 2025-26)

Year	Power generation from WHRB						Emission Factor tCO2eq/MWh	Net CO2 reduction achieved tCO2eq
	Capacity (in MW)	Operational days per year	Operational hours per day	Gross generation in MWH	Auxiliary consumption	Net generation in MWH		
2021-22	4.5	350	24	35919	4150	31769	1.390	44159
2022-23	6.5	350	24	28338	10039	18299	1.399	25601
2023-24	8	350	24	48199	24421	23778	1.399	33265
2024-25	8	350	24	44740	20931	23809	1.399	33309
2025-26	24	350	24	93900	9313	84587	1.399	118337
				251096	**68854**	**182242**		**254671**
Average CO_2 reduction per Year: 50934 tCO2eq								

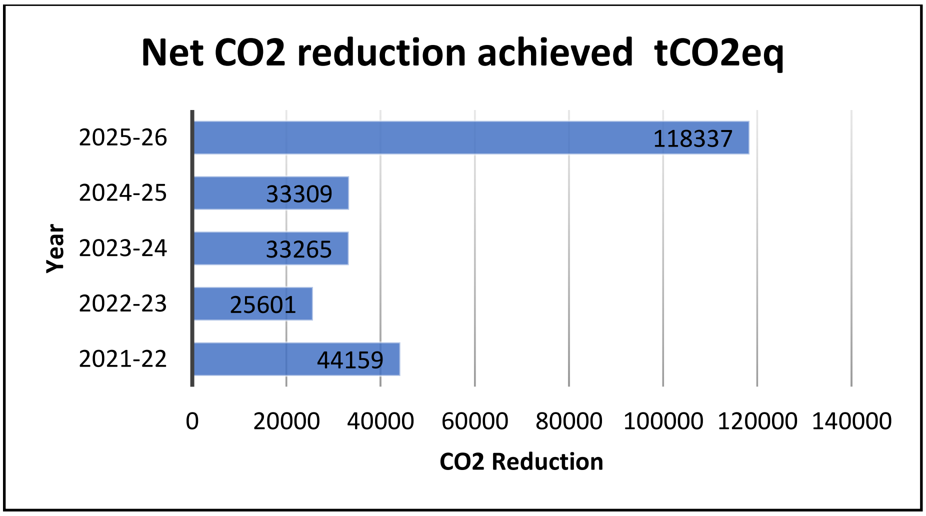
(Data source: ESG and energy department HPSL [29])

Capacity and Generation Growth: **(a)** Exponential Capacity Scaling: Operational capacity remained stable or grew modestly between 2021 and 2025 (4.5 MW to 8 MW) but saw a massive 200% capacity spike in 2025-26, jumping to 24 MW. (b) Energy Generation Volatility: Gross generation did not follow a perfectly linear trajectory. Despite a capacity increase in 2022-23 (to 6.5 MW), gross generation dropped to its lowest point (28,338 MWh), indicating potential plant underutilization, maintenance shutdowns, or lower thermal efficiency from primary heat sources during that fiscal year Other WHRB entities in India also validate comparable outcomes [30].

Auxiliary Consumption Efficiency: (a) The 2023-2025 Efficiency Bottleneck: In years 2023-24 and 2024-25, auxiliary power consumption peaked severely, draining 50.6% and 46.7% of gross generation respectively. This unusually high internal power usage significantly depressed net generation numbers. (b) Turnaround in 2025-26: The final year (2025-26) marked a massive optimization breakthrough. Auxiliary consumption fell to just 9.9% of gross generation (9,313 MWh out of 93,900 MWh), unlocking a record net generation of 84,587 MWh Similar outcomes are likewise verified by other CPP companies and organisations [30] [31].

Carbon Mitigation Metrics: Emission Factor Stability: The grid emission factor remained steady, minorly increasing from 1.390 to 1.399 tCO_2eq/MWh, reflecting the high-carbon baseline of the surrounding displaced grid electricity. Offset Peak: Driven by high net generation and low auxiliary loss, the year 2025-26 alone contributed 46.4% of the total 5-year carbon offsets (118,337 tCO_2eq), similar results are also authenticated by other entities [32] [33].

Figure 2: Net CO_2 reductions in 5 years



Technical Challenges: While the carbon abatement potential is significant, practical industrial implementation faces several technical challenges. Kiln waste gas contains heavy dust loads (35 - 40 g/Nm^3). This dust can cause severe abrasion and fouling on boiler tubes, requiring advanced soot-blowing systems. The CDM methodology adopted by other units also validated comparable outcomes in India [34] [35].

5. Strategic recommendations

➢ **Replicate the 2025-26 frameworks:** Audit the technical parameters of the 2025-26 cycles to ensure the <10% auxiliary power consumption rate is maintained as the standard operational baseline.

- **Monetization of carbon offsets**: The 254,671 tonnes of (CO_2) minimized presents an excellent baseline for registering under Carbon Credit markets (such as voluntary carbon markets or local compliance schemes), transforming environmental savings into a direct revenue stream.
- Kiln operations are driven by metallurgical production parameters rather than steam demands. This causes fluctuations in gas volume and temperature. Advanced automated control systems (such as PID or Genetic Algorithm tuning) are required in the post-combustion chamber to maintain steady power output.

5. Conclusion

This research paper quantified the thermodynamic viability and carbon mitigation potential of implementing Waste Heat Recovery (WHR) systems within the coal-based sponge iron industry under the regulatory framework of the Clean Development Mechanism (CDM). The empirical analysis demonstrates that capturing high-enthalpy rotary kiln flue gases provides a powerful dual pathway for industrial decarbonization. The findings indicate that the carbon mitigation impact is highly dependent on external variables, most notably the baseline emission factor of the regional grid. The deployment of WHRB systems has demonstrated exceptional scaling, expanding capacity from **4.5 MW to 24.0 MW** (a 433% increase). Over the five-year lifecycle, the facility successfully mitigated a **total of 254,671 tCO_2eq**, averaging an environmental offset of **50,934 tCO_2eq per year**. By converting waste heat into clean, captive electricity, sponge iron facilities can effectively mitigate severe localized thermal pollution while satisfying a major share of their internal electrical demand. From a climate policy perspective, the application of the UNFCCC baseline methodology ACM0012 provides a rigorous, transparent architecture to monetize these energy efficiency improvements.

In coal-dominant grids, the displacement of grid-purchased electricity by WHR systems yields significant, quantifiable reductions in greenhouse gas emissions, translating into a vital source of carbon financing through Certified Emission Reductions (CERs). However, this study also highlights that as national grids progressively transition toward renewable energy, the regulatory carbon value of fixed waste heat assets faces a linear decline, underscoring the urgency for immediate project deployment. Ultimately, accelerating the adoption of WHR systems is no longer merely an option for resource conservation; it is a vital prerequisite for the survival of the sponge iron sector in a net-zero economy. By pairing thermodynamic efficiency with market-based carbon instruments like the CDM, the industry can successfully bridge the gap between financial viability and aggressive environmental stewardship.

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