

# Minimizing Reboiler Energy Requirements for Post Combustion CO<sub>2</sub> Capture from Steel Industry Emissions

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**Abstract**— The iron and steel industry is among the largest contributors to global carbon dioxide (CO<sub>2</sub>) emissions. Post-combustion chemical absorption using amine-based solvents has emerged as a practical solution for mitigating CO<sub>2</sub> emissions. However, the high energy demand in the regeneration step remains a major barrier to large-scale deployment. In this study, an Aspen Plus process model was developed to simulate CO<sub>2</sub> capture from five steelmaking sub-processes: Sintering, Coke production, Lime production, Utility, and Metal production. Monoethanolamine was employed as the solvent at concentrations from 25 to 40 Wt.% with a fixed CO<sub>2</sub> loading of 0.25. The model was developed with absorber and stripper columns to achieve 85% CO<sub>2</sub> capture efficiency. Results indicate that reboiler duty values range from 3,342 to 4,136 kJ/kg of CO<sub>2</sub>, depending on the process type and solvent concentration. Increasing solvent concentration reduced by up to 10% with 35 – 40 Wt.% MEA, showing the favorable results between solvent flow rate and energy demand.

**Keywords**— Aspen Plus, Carbon Capture, Energy optimization, MEA solvent, Reboiler duty, Steel Industry.

## I. INTRODUCTION

Carbon dioxide (CO<sub>2</sub>) is the primary greenhouse gas driving anthropogenic climate change [1]. The iron and steel industry is one of the most carbon-intensive sectors, contributing approximately 7–9% of global CO<sub>2</sub> emissions, with emission factors ranging from 1.8 to 2.3 tonnes of CO<sub>2</sub> per tonne of steel produced [2]. Decarbonizing the steel sector is therefore crucial for achieving global climate goals [3]. Post-combustion CO<sub>2</sub> capture using amine-based solvents is one of the most feasible strategies for retrofitting existing industrial plants, including steelmaking units [4].

Among amines, monoethanolamine (MEA) is widely recognized for its fast kinetics and high capture efficiency and has been extensively modeled in process simulations [5]. However, MEA systems suffer from significant limitations, particularly high solvent energy regeneration, along with chemical degradation and corrosion—which strongly impact operational costs [3]. Optimizing reboiler duty is therefore fundamental for enhancing the economic viability of CO<sub>2</sub> capture systems [5]. Steelmaking involves multiple key processes, such as sintering, coke production, lime production, utility operations, and metal processing, each with distinct flue gas profiles. These variations influence solvent loading requirements and energy consumption during absorption and regeneration [6]. This study addresses this gap by developing an Aspen Plus rate-based model to simulate MEA-based CO<sub>2</sub> capture for five steel industry flue gas streams, with MEA concentrations from 25–40 wt.% and a fixed CO<sub>2</sub> loading of 0.25 mol/mol MEA, targeting 85% removal efficiency [6].

The core objective is to evaluate how solvent concentration affects reboiler duty across different steelmaking flue gases and to determine optimal operating ranges for energy efficiency.

## II. LITERATURE REVIEW

### A. CO<sub>2</sub> emissions from the iron and steel industry

Iron and steel processing plants are typically composed of ironmaking and steelmaking processes. The ironmaking process involves preparing raw materials and melting the materials to be used for producing hot metal (or pig iron), which refers to the process of making pure liquid iron from hot and scrap metals using an electric arc furnace. Additionally, continuous casting and rolling processes are performed to produce solid steel products. A utility plant is also introduced to supply steam and power to the process. Most of the CO<sub>2</sub> emitted by the iron and steel industry is generated during the ironmaking process and at utility plants. Excluding the amount of CO<sub>2</sub> emitted through flaring and transportation, 48.7% and 48.0% of the total CO<sub>2</sub> emissions are emitted from the utility power plant and the ironmaking process, respectively [7]. Therefore, in this study, the ironmaking process and utility power plant were selected as the targets for the economic evaluation of the CO<sub>2</sub> capture process for the iron and steel industry.

The general ironmaking process consists of subprocesses such as metal production, sintering, coke production, lime production, and utility [7]. A simplified block flow diagram is shown in Fig. 1, although the process is highly integrated between subprocesses in practice. The sintering process

produces a homogeneous raw material called sinter, which is then fed to a blast furnace for the manufacture of hot metal (pig iron) through a metal production process [8]. Coke from the coke production process is supplied as fuel, along with sinter, and is also used as a reducing agent. Limestone is added as an auxiliary material to remove impurities by forming a mixture of impurities, often referred to as slag. The utility process is introduced to produce the steam and electricity required by iron and steel processing plants. Boilers and steam turbines typically produce heat and electricity. Natural gas and by-product gases from iron and steel processes, such as blast furnace gas, are commonly used as fuels.

This supply of thermal energy is one of the primary sources of CO<sub>2</sub> emissions in the iron and steel industry. Conventional power generation plants, such as coal-fired and NGCC power plants, emit exhaust gas from boilers or gas turbines from a single emitting point, and the flue gas composition is relatively constant. From studies conducted by DOE/NETL [9], flue gases containing approximately 12.8 and 3.9 mol% of CO<sub>2</sub> are emitted from coal-fired and NGCC power plants, respectively. However, in iron and steel plants, exhaust gases are generated from different subprocesses in a non-centralized and dispersed manner. In addition, the composition of exhaust gas also differs because there are differences in the raw materials and fuels used for each emission source. Blast furnace gas (BFG) from the blast furnace of the metal production process and air are supplied to the coke oven.

TABLE I. Specification of flue gases from the iron and steel industry for CO<sub>2</sub> capture.

CO <sub>2</sub> emission sources	Sintering process	Coke production process	Lime production process	Utility process	Metal production process
Flowrate (kg/s)	57.64	110.19	32.08	338.13	139.3
Temperature (K)	393	523	403	423	413
Pressure (bar)	1.03	1.03	1.03	1.03	1.11
Mole fraction					
CO <sub>2</sub>	0.0481	0.1477	0.1941	0.2643	0.2730
CO	0.074	-	-	-	-
O <sub>2</sub>	0.1490	0.0500	0.0777	0.0777	0.0080
N <sub>2</sub>	0.7265	0.6947	0.6024	0.6588	0.6552
H <sub>2</sub> O	0.0690	0.1075	0.1256	0.0698	0.0638

During coke production, flue gas containing approximately 14.8 mol% of CO<sub>2</sub> is emitted. This coke oven gas (COG, by-product gas) also contains methane and hydrogen, which are supplied to the sinter and lime production processes. Off-gas containing approximately 4.8 mol% of CO<sub>2</sub> is emitted from the sinter process, while exhaust gas containing approximately 19.4 mol% of CO<sub>2</sub> is emitted from the lime production process. Finally, exhaust gas containing approximately 27.3% of CO<sub>2</sub> is emitted through a hot stove during the metal production process. In this study, an iron and steel process producing four million tonnes of hot rolled coil (HRC) per year was selected as a reference plant.

To evaluate the economics of CO<sub>2</sub> capture, exhaust gases emitted from five different subprocesses were selected (Fig. 1). The conditions of exhaust gases emitted to the stack after being treated for air pollutants were chosen for the analysis, which are summarized in Table 1 [7].

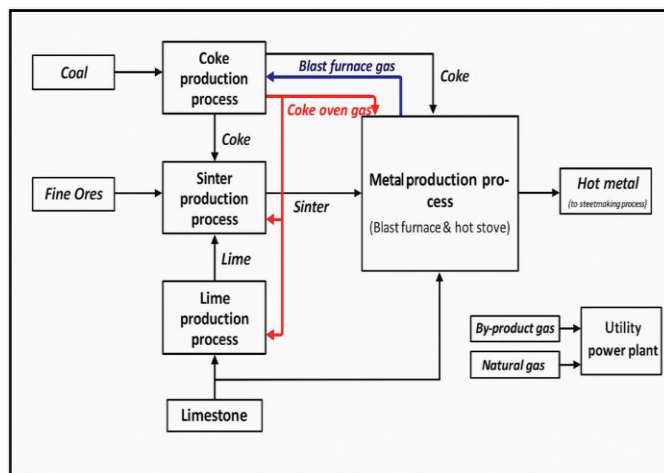


Fig. 1. Block diagram of the iron-making process in an iron and steel processing plant

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### B. Post Combustion CO<sub>2</sub> Capture with MEA

Monoethanolamine (MEA) remains the benchmark solvent for post-combustion CO<sub>2</sub> capture due to its high reactivity and mature commercial use [10]. However, MEA capture systems are energy-intensive, with regeneration energy often accounting for 60-70% of total process costs. Typical values range from 3.1 to 3.8 MJ/kg CO<sub>2</sub> for industrial flue gases.

### C. CO<sub>2</sub> Capture in the Steel Industry

Compared to power and cement plants, fewer studies focus on the steel industry's CO<sub>2</sub> capture. Choi et al. (2019) developed an MEA-based process model for five steel plant flue gases, highlighting strong variation in reboiler duty depending on CO<sub>2</sub> concentration [11]. Biermann et al. (2019) investigated the use of excess heat from steel mills to offset capture energy penalties [12], while Feng et al. (2023) reported capture case studies in Chinese integrated steel enterprises [13]. Perpiñán et al. (2023) reviewed CCS integration in blast furnace steelmaking, emphasizing technical and economic challenges [14].

### D. Simulation and Optimization Studies

Rate-based Aspen Plus models have been widely applied to predict absorber–stripper performance and optimize operating parameters. Udara Arachchige et al. (2020) simulated CO<sub>2</sub> capture across various industries, reporting reboiler duties in the range of 3.1–3.7 MJ/kg CO<sub>2</sub>, and highlighting solvent concentration as a critical factor [6].

### E. Research Gap

Although significant progress has been made, most prior research focuses on either single sub-processes (e.g., sinter gas or blast furnace gas) or general capture cost analyses. Few studies systematically compare reboiler duty across multiple steel sub-processes under consistent MEA solvent conditions. Moreover, the effect of varying MEA concentration (25–40 wt%) on reboiler duty in steel flue gases has not been extensively quantified. This study addresses this gap by developing an Aspen Plus rate-based model for the major flue gas streams of the steel industry and evaluating the effect of solvent concentration on regeneration energy.

### III. PROCESS DESCRIPTION

The absorption-solvent regeneration process, reported in Fig. 2, was considered in this work. The plant is divided into two interconnected sections: the absorption, where the target component is transferred from the gas to the liquid phase, and the stripping, used to recover the mass separation agent. In the absorption section, the CO<sub>2</sub>-rich flue gas is sent to the bottom of the absorber, where it flows counter-current with the liquid solvent. The exhaust gas exits from the top of the column and is sent to the stack. The CO<sub>2</sub>-rich solvent from the bottom of the absorber is pumped to a cross heater, where its temperature is increased, and then to the top of the stripper. The liquid flows counter-current to the vapor flow generated by the reboiler. In this case, the CO<sub>2</sub> is transferred from the liquid phase to the vapor phase. From the top of the stripper, a gaseous stream, composed mainly of CO<sub>2</sub> and water, is sent to a partial condenser where the CO<sub>2</sub> is concentrated in the gas phase. The lean solvent exiting the stripper bottom is partly vaporized in the reboiler and then sent to the mixer, where we add the degraded water and solvent using a makeup stream. Then further cooled and recycled to the top of the absorber. This configuration differs from the classic absorption-solvent regeneration process [15][16], since the stripper was considered, a column configuration without reflux from the condenser was used to avoid unnecessary energy consumption. This choice was made for energy-saving reasons. The absorber and stripper are both packed columns rather than plate ones because the packing offers a larger contact surface. In this work, Monoethanolamine was used as a solvent, as it is the most studied and proven to be the most mature one for this process [17].

### A. Thermodynamics and chemical reactions

#### a. Chemical Reactions

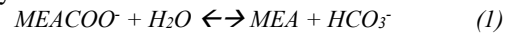
TABLE II. Constant values of the equilibrium constant equation (6)

Parameter	Reaction 1	Reaction 2	Reaction 3	Reaction 4	Reaction 5
A <sub>j</sub>	-0.52	231.46	216.05	-3.038	132.89
B <sub>j</sub>	-2545.53	-12092.1	-12431.7	-7008.3	-13445.9
C <sub>j</sub>	0	-36.78	-35.48	0	-22.47
D <sub>j</sub>	0	0	0	-0.00313	0

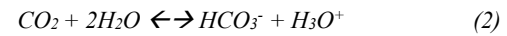
Carbon dioxide and monoethanolamine reacting system, CO<sub>2</sub> is solubilized in the liquid phase either as carbamate, carbonate or bicarbonate form. The most important chemical

reactions are given in Eqs (1)-(5) [18]. Hose contact values A-D for the reactions which are given in equation 1-5 are tabulated and represent in Table.

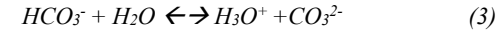
Hydrolysis reaction:



Dissociation of dissolved carbon dioxide:



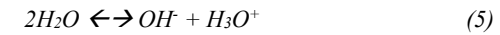
Dissociation of bicarbonate:



Dissociation of protonated MEA:



Ionization of water:



The mole fraction of each component is calculated using the above equations. The equilibrium constant, which is required for the calculations, has been calculated using Eq. (6)

$$\ln K_j = A_j + B_j/A + C_j \ln T + D_j/T \quad (6)$$

#### b. Model development

The carbon capture model is developed for the major flue gas streams from the iron and steel industry, including the sintering, coke production, lime production, utility operations, and metal processing [7]. The Aspen Plus rate-based model is used to develop the comprehensive process flow sheet (Fig. 2). The process flow diagram is developed to capture 85% of CO<sub>2</sub> from the flue gas stream. Absorber and stripper are considered as the main two-unit operation blocks in the capture process. Inlet flue gas and the solvent are supplied at 313 K, and the absorption process is performed at 1 bar pressure for optimum operation.

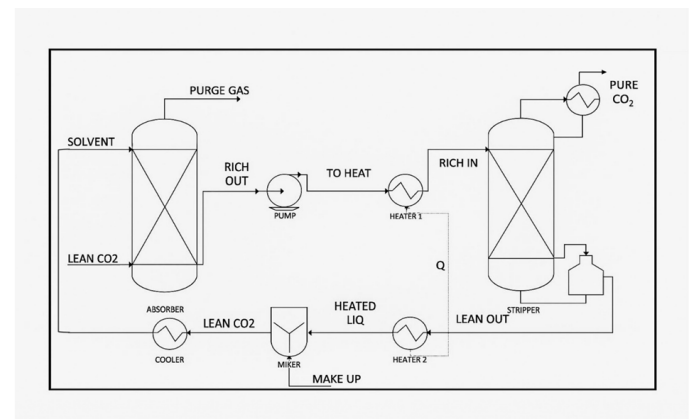


Fig. 2. Process Flow Diagram

TABLE III. Solvent stream parameters

Parameter	Sintering process	Coke production process	Lime production process	Utility process	Metal production process
Flow rate (kg/s)	59	378.8	127	1887.5	678
CO <sub>2</sub> lean loading (mole CO <sub>2</sub> /mole amine)	0.25	0.25	0.25	0.25	0.25
Solvent concentration (w/w%)	40	40	40	40	40

The rich solvent leaving the bottom of the absorber column is heated up to 382 K using a heater unit before sending it to the stripper section. The stripper is operating at 2 bar absolute pressure. The solvent stream is selected based on previous studies [19]. The solvent stream condition, which is used to perform the simulation studies, is given in Table 3. The amine-based carbon capture process is implemented in Aspen Plus process simulation software as shown in Fig. 2.

TABLE IV. Aspen Plus model specifications of absorber and stripper column

Specification	Parameter value	
	Absorber	Stripper
Number of stages	15	15
Operating pressure	1 bar	2 bar
Reboiler	None	Kettle
Condenser	None	None
Packing Type	Mellapak, Sulzer, Standard.250Y	Flexipac.Koch, metal 1Y
Packing height	20m	18m
Packing diameter	15m	12m
Mass transfer coefficient	Bravo et al. (1985) [22]	Bravo et al. (1985) [22]
Interfacial area method	Bravo et al. (1985) [22]	Bravo et al. (1985) [22]
Interfacial area factor	1.5	2
Heat transfer coefficient method	Chilton and Colburn	Chilton and Colburn
Holdup correlation	Billet and Schultes	Billet and Schultes
Film resistance	Discrxn for liquid film and Film for vapor film	Discrxn for liquid film and Film for vapor film
Flow model	Mixed	Mixed

Monoethanolamine (MEA) is considered as the solvent, which is used for the absorption process. The main drawback of the MEA based carbon capture process is a high amount of energy requirement in the regeneration process, that is, the reboiler duty in the stripper column. Hence, the optimization of the capture plant is required to install the carbon capture process in real industrial applications. Absorber and Stripper packing conditions and operating parameters are selected from the literature to perform the simulation studies (Table 4) [20][21].

#### IV. RESULTS AND DISCUSSION

##### A. Effect of MEA concentration on reboiler duty

Summarize Table 5–9 the variation of reboiler duty with MEA solvent concentration for the five steelmaking sub-processes. Across all cases, a consistent decreasing trend is observed as solvent concentration increases from 25 to 40 wt%. At low concentration (25 wt%), reboiler duty values exceeded 4100 KJ/kg of CO<sub>2</sub> for some streams, whereas at 40 wt% MEA the values declined to as low as 3342 KJ/kg of CO<sub>2</sub>. These results are in agreement with published studies that reported improved energy efficiency with higher amine strength due to reduced solvent circulation and enhanced absorption capacity based on the previous work [6].

The study deliberately limited solvent concentrations to the 25–40 wt % range. Concentrations above 40 wt % were not considered because, although higher amine strengths can theoretically increase single-pass CO<sub>2</sub> absorption, they

introduce significant practical and operational challenges. Specifically:

- Viscosity increase: Higher amine concentrations cause a sharp rise in solution viscosity, which reduces gas–liquid mass-transfer efficiency and decreases absorber performance.
- Hydraulic issues: Elevated viscosity and carbamate formation increase the risk of column flooding, poor liquid distribution and foaming, which leads to compromising overall process stability.
- Corrosion and degradation: Stronger amine solutions are more prone to thermal degradation and equipment corrosion, raising maintenance needs and operational costs.
- Energy penalty: Higher concentrations increase the sensible heat load during regeneration, which can offset any gains in CO<sub>2</sub> loading and increase specific reboiler duty (Xu et al., 2021).

Therefore, the 25–40 wt % range represents a carefully chosen, industrially validated balance between CO<sub>2</sub> capture efficiency, energy consumption, and reliable operation [1][5][10]. This range is consistent with prior studies, confirming it as the practical upper limit for stable post-combustion CO<sub>2</sub> capture operations.

TABLE V. Reboiler duty for the sintering process at different MEA concentrations

Parameters	Sintering Process			
MEA Wt%	25	30	35	40
Reboiler Duty	3750.6	3622.5	3565.9	3520.4

TABLE VI. Reboiler duty for Coke production process at different MEA concentrations

Parameters	Coke production process			
MEA Wt%	25	30	35	40
Reboiler Duty	4136	3905.1	3788.6	3695.7

TABLE VII. Reboiler duty for lime production process at different MEA concentrations

Parameters	Lime Production Process			
MEA Wt%	25	30	35	40
Reboiler Duty	3804.3	3615	3511.4	3432.9

TABLE VIII. Reboiler duty for the utility process at different MEA concentrations

Parameters	Utility process			
MEA Wt%	25	30	35	40
Reboiler Duty	4105.4	3953.7	3796.6	3636.3

TABLE IX. Reboiler duty for Metal production process at different MEA concentrations

Parameters	Metal production process			
MEA Wt%	25	30	35	40
Reboiler Duty	3781.9	3698	3447.2	3342.1

##### B. Industrial applicability and scale-up considerations

The simulations were specifically configured to represent a 500 MW-equivalent integrated steel plant, with flue-gas composition and flow rates typical of modern steel production (CO<sub>2</sub> ~20–25 vol%, N<sub>2</sub> ~70 vol%, O<sub>2</sub> ~5–6 vol%). Rate-based absorber and stripper models were employed using validated mass- and heat-transfer correlations, ensuring that solvent performance, CO<sub>2</sub> loading, and reboiler duty are representative

of real industrial conditions. Although certain site-specific factors (e.g., SO<sub>x</sub>/NO<sub>x</sub> impurities, dust, and local fouling) were not explicitly modelled, the simulation framework captures the key thermodynamic and kinetic behaviour of MEA systems. The relative solvent performance and optimized concentration ranges identified here are expected to hold under industrial operation, while absolute energy requirements may vary depending on plant-specific conditions. Furthermore, the predicted reboiler duty values (3300–4100 kJ/kg CO<sub>2</sub>) fall within ranges reported in pilot- and industrial-scale studies [10][1], confirming the practical relevance and scalability of the results. We also emphasize that future work, including pilot-scale validation and techno-economic analysis, will further confirm full-scale applicability.

### C. Industrial implications

The results indicate that operating with 35–40 wt.% MEA provides the most energy-efficient balance for solvent regeneration across all steelmaking processes. At these concentrations, reboiler duty values fall within the lower end of the reported industrial range (3.3–3.8 MJ/kg CO<sub>2</sub>), making capture more viable. For large-scale deployment, further reductions can be achieved by integrating waste heat recovery from steel plants or by adopting advanced process configurations such as intercooling, lean vapor compression, or rich-split arrangements. In addition, amine blends (e.g., MEA–PZ, MDEA–PZ) have demonstrated potential energy savings of up to 25–30% compared to standard MEA systems [23]. These strategies highlight clear pathways for improving the feasibility of CO<sub>2</sub> capture in the iron and steel industry.

### V. CONCLUSION

This study developed a rate-based Aspen Plus model to evaluate post-combustion CO<sub>2</sub> capture using MEA solvents from five key steel industry flue gas streams: sintering, coke production, lime production, utility boilers, and metal production. The following conclusions can be drawn:

- MEA concentration strongly influences reboiler duty. Increasing solvent concentration from 25 to 40 wt% reduced regeneration energy by up to ~10%, with optimal performance observed at 35–40 wt%.
- Flue gas characteristics affect capture energy demand. High-CO<sub>2</sub> streams (metal and lime production) exhibited the lowest reboiler duties (3342–3433 kJ/kg CO<sub>2</sub>), while low-CO<sub>2</sub> and high-flow streams (coke ovens and utility boilers) required higher duties (>4100 kJ/kg CO<sub>2</sub> at 25 wt%).
- Simulation results align with published industrial ranges. The overall reboiler duty (3.3–4.1 MJ/kg CO<sub>2</sub>) is consistent with values reported in previous MEA-based studies.
- Process optimization opportunities remain. Integration with waste heat recovery, advanced process configurations (e.g., intercooling, rich-split), and blended amine solvents (MEA–PZ, MDEA–PZ) can further reduce regeneration energy by 20–30%, improving industrial feasibility.

- The selected 25–40 wt % MEA range represents a practical upper limit for stable operation. Concentrations above this threshold, while increasing theoretical CO<sub>2</sub> capacity, may cause excessive viscosity, mass-transfer resistance, and corrosion. The simulation framework and results are scalable to industrial operations, with future pilot validation.

Overall, this work provides one of the first systematic comparisons of reboiler duty across multiple steel industry flue gas sources under consistent MEA conditions. The findings highlight both the challenges and opportunities for scaling CCS in the steel sector, and suggest that solvent management combined with process integration is essential for future decarbonization of this energy-intensive industry.

### REFERENCES

- [1] K. Li, A. Cousins, H. Yu, P. Feron, M. Tade, W. Luo, J. Chen, *Energy Sci. Eng.* 4, 23 (2016)
- [2] A. Hasanbeigi, L.K. Price, M. Arens, Emerging energy-efficiency and carbon dioxide emissions-reduction technologies for the iron and steel industry, International Energy Analysis Department, Energy Analysis and Environmental Impacts Division (2013)
- [3] C. Ruiz, De-carbonizing hard-to-abate sectors with renewables: G7 perspectives (2024)
- [4] A. Mio, L. Petrescu, A.V. Luca, S.C. Galusnyak, M. Fermeglia, C.C. Cormos, *Chem. Biochem. Eng. Q.* 36, 255 (2022)
- [5] G.T. Rochelle, *Science* 325, 1652 (2009)
- [6] U.S.P.R.A. Udara, R. Kohilan, M.A.L. Lakshan, M.K.L. Madalagama, P.R.P. Pathirana, P.W.S. Sandupama, *Energy Rep.* 6, 659 (2020)
- [7] IEAGHG, Iron and steel CCS study (Techno-economics integrated steel mill) (accessed Sep. 3, 2025)
- [8] P. Cavaliere (Ed.), *Ironmaking and steelmaking processes: greenhouse emissions, control, and reduction* (Springer, Switzerland, 2016)
- [9] DOE/NETL, Cost and performance baseline for fossil energy plants, Vol. 1a: Bituminous coal (PC) and natural gas to electricity, Revision 3 (2015)
- [10] R. Dugas, G.T. Rochelle, *Energy Procedia* 1, 1163 (2009)
- [11] J. Choi, H. Cho, S. Yun, M.G. Jang, S.Y. Oh, M. Binns, J.K. Kim, *Energy* 185, 971 (2019)
- [12] M. Biermann, Partial Carbon Capture—An Opportunity to Decarbonize Primary Steelmaking: A Techno-Economic Assessment of Amine Absorption of Carbon Dioxide at an Integrated Steel Mill, Master's thesis, Chalmers Tekniska Hogskola, Sweden (2019).
- [13] C. Feng, R. Zhu, G. Wei, K. Dong, T. Xia, *Appl. Energy*, 336, 120790 (2023).
- [14] J. Perpiñán, M. Bailera, B. Pena, P. Kannan, V. Evely, L.M. Romeo, *J. CO2 Util.*, 78, 102634 (2023).
- [15] R.K. Sinnott, Coulson & Richardson chemical engineering, Vol. 6: Chemical engineering design, 4th ed. (Elsevier Butterworth-Heinemann, 2005)
- [16] J. Seader, E. Henley, D. Roper, *Separation process principles* (1998)
- [17] F.A. Tobiesen, O. Juliussen, H.F. Svendsen, *Chem. Eng. Sci.* 63, 2641 (2008)
- [18] S. Freguia, Modeling of CO<sub>2</sub> removal from flue gases with monoethanolamine, Master thesis, Univ. of Texas, Austin (2002)
- [19] U.S.P.R. Arachchige, M. Mohsin, M.C. Melaaen, *Int. J. Energy Environ.* 3, 861 (2012)
- [20] Aspen Plus, Rate based model of the CO<sub>2</sub> capture process by MEA using Aspen Plus (Aspen Technology Inc., Cambridge, MA, USA, accessed Aug. 30, 2025)
- [21] A. Mohammad, Carbon dioxide capture from flue gas (PhD thesis, Delft University of Technology, Delft, Netherlands, 2009)
- [22] J.L. Bravo, J.A. Rocha, J.R. Fair, *Hydrocarbon Process.* 64, 91 (1985)
- [23] R. Sakwattanapong, A. Aroonwilas, A. Veawab, *Ind. Eng. Chem. Res.* 44, 4465 (2005)