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Optimization in Carbon Capture processes: Evaluating Heat Pumps for enhanced efficiency

Orsetti A., Ferrari. F.E.G.

NextChem Tech, Rome, Italy

a.orsetti@nextchem.it

The widespread adoption of Post-Combustion Carbon Capture (PCCC) technologies is critical for decarbonizing industrial production and reducing greenhouse gas emissions. However, these systems are often energy-intensive, particularly in the regeneration step, where thermal energy is required to release the captured CO₂ from the solvent. The energy demand for steam generation remains one of the key challenges for widespread implementation, particularly in scenarios with limited access to low-carbon steam.

This study explores the role of heat pumps as a viable solution for improving the energy balance of carbon capture systems. By leveraging waste heat recovery from flue gas streams, heat pumps can supply the thermal energy needed for solvent regeneration while significantly reducing energy losses. Compared to traditional steam-based regeneration methods, this approach enables a more efficient and electrified carbon capture process, aligned with renewable energy sources.

A techno-economic analysis is conducted to compare the performance of heat pump integration with conventional steam heating systems. The results indicate that heat pumps not only reduce operational emissions but also lower energy costs while maintaining system flexibility. Furthermore, their ability to recover and repurpose low-grade heat offers a scalable solution for industrial applications, particularly where carbon neutrality goals are prioritized.

NextChem's optimized design for heat pump integration demonstrates the potential for complete electrification of carbon capture systems, minimizing indirect emissions and reducing reliance on fossil fuels. This innovation represents a critical step toward sustainable and cost-effective carbon capture technologies, supporting industries in achieving ambitious decarbonization targets and addressing global climate challenges.

* 1. Introduction

The Global Risks Report 2024 [1] identified climate change as the principal challenge the world will face over the next decade. In response, the European Union has committed to achieving carbon neutrality by 2050. This objective is not only outlined in the European Green Deal [2], but has also been enshrined as a legally binding obligation under the European Climate Law [3]. Achieving this target requires the use of all available tools. The Intergovernmental Panel on Climate Change (IPCC) states that emission reductions alone will not be sufficient to reach net zero by 2050. The IPCC stated in a report that “All available studies require at least some kind of carbon dioxide removal to reach net zero; that is, there are no studies where absolute zero or even CO2 emissions are reached by deep emissions reductions alone”. [4]

Carbon capture can achieve negative emissions when biogenic carbon sources are used in the process. It may also play a role in decarbonizing processes classified as “hard to abate,” which refers to sectors and industries where avoiding CO₂ emissions is particularly difficult or impossible. Examples of hard-to-abate industries include cement, steel, and chemicals.

Industrial Carbon Capture and Storage (CCS) can remove 90–99% of CO₂ emissions from industrial plants, addressing both energy-related and process emissions. Although the deployment of CCS technology in the industrial sector has been limited so far, it has the potential to achieve substantial reductions in greenhouse gas (GHG) emissions from industry.

Among the available Carbon Capture (CC) technologies, chemical absorption processes are recognized as proven and deployment-ready solutions for capturing CO₂ from diluted gas streams [6] and Amine-based CC is noted for its maturity and versatility. In Post-Combustion CO₂ Capture, Carbon Dioxide is extracted from the flue gas of conventional plants after complete fuel combustion. At this stage, CO₂ is separated from a mixture primarily composed of nitrogen (N₂), water vapor (H₂O), oxygen (O₂), and trace components like NOx and SOx. Reactive amine absorption technologies have a history of use in purifying natural gas and industrial gas streams, particularly for removing acid gases such as CO₂ and H₂S. This operational experience has facilitated the application of these processes to flue gas treatment.

Performance indicators for carbon capture design include regeneration energy. Typically, CO₂ capture units use heat (usually from steam) and electricity, where the largest contributor to the regeneration energy is the duty at the reboiler. The Key Performance Indicator (KPI) commonly used is the energy required per unit of CO₂ captured. Efforts are being made to reduce this specific KPI, making Carbon Capture more economically viable.

The goal of this document is to highlight how recovering heat in the flue gas using a heat pump can significantly reduce the energy required per unit of CO₂ captured and increase the thermal efficiency of the overall process.

* 1. Process Description
		1. Post-Combustion Amine Carbon capture

The Amine Carbon Capture Unit examined in this paper comprises three primary sections: Flue Gas Pretreatment, CO₂ Absorption, and Solvent Regeneration. Additionally, the amine absorption unit may include various auxiliary units that ensure efficient and sustained operation, such as Filter Units, Heat Recovery Systems, and Reclaiming Systems.

In the Flue Gas Pretreatment section, a Direct Contact Cooler (DCC) is utilized to reduce the flue gas temperature by directly mixing it with a cooling liquid, commonly quenching water. This process involves the interaction of flue gas with the quenching water, which absorbs heat from the gas, thereby lowering its temperature. The cooled water is generally recirculated through an external loop, where it is further cooled, often using cooling water.



Figure 1 - Schematic representation of amine carbon capture unit [7]

Following initial cooling, the flue gas enters the absorption column from the bottom with the aid of a blower to mitigate the pressure losses along the flue gas path. As the gas ascends the column, CO₂ is absorbed by an aqueous amine solvent in a counter-current flow arrangement. The column is equipped with random or structured packing materials to enhance the contact between the gas and liquid phases. At the top of the absorber, a washing section is incorporated to minimize solvent carryover by contacting the gas with cold water. The treated flue gas is then expelled from the top, while the CO₂-rich solution is collected at the bottom and pumped to the regenerator. In the regenerator, the solution passes through a heat exchanger to pre-heat it before entering the main regeneration stage.

In the regenerator the CO₂-rich solution flows downward, where CO₂ is removed and separated at the column's top. The reboiler produces stripping vapor supplying heat for amine regeneration, while low-pressure steam transfers its latent heat to the solution. At the top of the column the CO₂ gas is cooled and separated, returning the water to the regenerator. The separated CO₂ gas can then be dehydrated and compressed as needed.

* + 1. Heat Pump

Unlike traditional heating systems that generate heat by burning fuel, a heat pump transfers heat using a working fluid which undergoes phase changes between liquid and gas. The primary components of a heat pump include the evaporator, compressor, condenser, and expansion valve.

In the evaporator, the working fluid absorbs heat from a low-temperature source and evaporates into a gas as it absorbs thermal energy. The refrigerant gas is then compressed by the compressor, raising its temperature and pressure. This process requires electrical energy.

The hot, high-pressure refrigerant gas flows into the condenser, where it releases the absorbed heat to a target space. During this step, the refrigerant condenses back into a liquid.

The liquid refrigerant passes through an expansion valve that reduces its pressure and temperature, preparing it to absorb heat again in the evaporator. This cycle repeats continuously to move heat from a colder area (heat source) to a warmer area (heat sink).

The efficiency of a heat pump is measured by its Coefficient of Performance (COP), which represents the ratio of heat transferred to the energy consumed. Heat pumps are highly efficient because they transfer heat rather than generate it, making them a sustainable solution for heating and cooling.

* + 1. Post-Combustion Amine Carbon capture with Heat Pump integration

Amine-based Carbon Capture technology faces major challenges in its application due to the high steam consumption needed for solvent regeneration, which can make up to 40% of a CO2 capture plant’s operating cost [8]. Many facilities, especially in hard-to-abate industries, lack readily available steam, leading to extra energy demands and costs if steam must be generated specifically for carbon capture regeneration. Using steam from an upstream process can decrease overall plant efficiency and energy production, while generating steam on purpose also raises CO₂ emissions, since industrial plants often burn fuel gas or hydrocarbons for steam production, thus reducing actual CO₂ removal efficiency.To achieve the target net CO₂ capture (the difference between the CO₂ captured and the CO₂ emitted to generate steam), the carbon capture system must be overdesigned to handle also the extra CO₂ generated for steam production. Neglecting this consideration would result in a net capture lower than expected.

One proposed solution is to electrify the boiler and use green power to generate steam, which would eliminate the emissions associated with steam production. However, with this approach the overall capital expenditure (CapEx) and operational expenditure (OpEx) would increase significantly, as electric boilers are inefficient beyond a certain design capacity, and the cost of green energy would be higher than that of conventional steam production.

The alternative solution involves recovering the waste heat from the Direct Contact Cooler (DCC), despite it being available at lower temperatures. To make this feasible, a heat pump supplied by renewable power (in order to have net zero emission linked to power production), can be used to transfer this heat to the solvent regeneration section. In most cases, the heat duty required to cool the flue gas exceeds the duty needed at the reboiler, making it possible to avoid steam production altogether.

NextChem's proposed Heat Pump Unit would recover heat from the Flue Gas Quencher's circulating water and supply it to the reboiler for solvent regeneration.

In figures 2 and 3 are reported typical BFD for CO2 capture with or without the Heat Pump.



Figure 2 - Typical CO2 Capture BFD



Figure 3 - CO2 Capture with Heat Pump BFD

The Heat Pump Unit uses a refrigeration cycle with a service fluid to transfer heat from a heat source at low temperature to a heat sink at higher temperature. Common hydrocarbon refrigerants like propane or butane can be used as service fluid, depending on temperature levels or project needs. In Carbon Capture systems, the heat sink can be the Reboiler at the Regenerator's bottom, and the heat source is the heat exchanger in the Flue Gas DCC.

The cold service fluid is heated and vaporized in the evaporator by exchanging heat with the circulating water in the DCC. After that, the service fluid is compressed in the Compressor. The final pressure level enables the service fluid to condense through exchange with the lean solvent at the bottom of the Regenerator. The liquid service fluid is ultimately laminated and brought to the initial conditions.

* 1. Carbon capture overdesign

As qualified in the previous paragraph, Amine-based Carbon Capture systems are known to face significant challenges, primarily due to the high steam consumption required for solvent regeneration. An often-overlooked factor is the additional CO₂ emissions generated from the production of steam itself, particularly in facilities that burn fuel gas or hydrocarbons. The need to capture CO₂ emissions from steam production can lead to the overdesign of the carbon capture system, necessary to account for the additional CO₂ generated by the boiler. In many industrial plants, natural gas is used as the fuel gas, producing CO₂ during combustion and the system must be scaled up to handle effectively these additional emissions.

Figure 4 – Overdesign of the Carbon Capture Unit with methane steam boiler

The energy required for solvent regeneration plays a critical role in determining the extent of overdesign. In a typical carbon capture plant, the solvent regeneration process requires a significant amount of heat, usually provided by steam. If the CO₂ emissions from steam production are not considered, the design of the carbon capture system may be insufficient. The provided graph illustrates the calculated overdesign for a generic carbon capture plant based on the varying energy requirements for solvent regeneration. Key assumptions for this analysis include: the boiler's efficiency is 85%, the fuel gas used is pure methane (CH₄), which produces CO₂ in stoichiometric quantities, and the CO₂ capture efficiency is 90%.

The overdesign resulting from the need to capture CO₂ emissions coming from steam production can lead to increased capital expenditure (CapEx) and operational expenditure (OpEx). If hydrocarbons heavier than methane are used, the increment is even higher.

* + 1. Case study methodology

We present some data from a case study of carbon capture in a cement plant designed to capture and liquefy 1600 MTPD of CO2, comparing three different scenarios. In Case A, a boiler is installed to produce steam from natural gas (methane), but the CO₂ emissions generated by the steam boiler are not captured, and thus, the required CO₂ capture target (1600 MTPD) is not met. In Case B, a heat pump is used to provide the necessary duty for the regenerator, achieving the required CO₂ capture target. In Case C, the steam boiler is used again, but the carbon capture system is designed to also capture the additional CO₂ emissions produced by the boiler. The CO2 captured in the case study has to be liquefied and sent to sequestration. All costs associated with liquefaction (CapEx and OpEx) have been included in the analysis, considering a traditional ammonia refrigeration cycle and the liquid CO2 storage, with the relevant boil-off management.

Table 1: Case Study input data

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | Case A | Case B | Case C |
| Heat Media |  | Steam | Heat Pump | Steam |
| Unit Design (CO2 Captured) | MTPD | 1600 | 1600 | 1600+20% |
| Net CO2 Captured | MTPD | 1600 | 1300 | 1600 |
| Amine Energy Requirement | GJ/tCO2 | 2.9 | 2.9 | 2.9 |
| Required Storage | Tons | 15,000 | 15,000 | 15,000+20% |

The cost estimate follows Class 4 Cost Estimate guidelines recommended by AACE International [9]. (Typical accuracy range: -30% to +50%). Costs for Carbon Capture unit and Utilities are based on equipment cost, while the CO2 liquefaction and storage costs are derived from budgetary quotations from specialized suppliers. Bulk materials such as piping, instrumentation and control, electrical, steel structures, spare parts for commissioning, first fill of catalysts and chemicals, transportation and construction are estimated using NextChem's in-house database and references. Plant site has been considered in northern Europe where many Carbon Capture initiatives are taking place.

The amine energy requirement has been conservatively considered constant even though the flue gas coming from steam boiler would dilute the concentration of the CO2 in the flue gas sent to the amine carbon capture unit and increase the costs per unit of CO2 of Case C.

* + 1. Case study results

Investment costs for the three solutions have been compared: Case B has a slightly higher CapEx than Case A. This happens since the heat pump system has a higher installation cost than the steam boiler, given the same duty to be provided to the reboiler. However, compared to Case C, Case A has a lower CapEx due to the overall system overdesign. In Case C, the overdesign of the utilities system to produce more cooling water and the Boiler Feed Water necessary for steam production has also been included. Figure 5 shows the breakdown of the different units on the total capital expenditure (CapEx) and provides a comparison between the three cases.



Figure 5 – Capex for Case Study

The operating expenses (OpEx) have been calculated in order to evaluate the impact of the heat pump. The power requirements for carbon capture, CO2 liquefaction and storage, as well as utilities production, have been considered and included in the calculation. Considering that the COP values of available technologies range between about 2.4 and 5.8 with a temperature lift of 95 to 40 K [10] for the Case Study a COP of 3 has been considered. Input data for Case C have been taken as per Paragraph 3 and the resulting data are shown in Table 2:

Table 2: Case Study output data

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | Case A | Case B | Case C |
| Heat Media |  | Steam | Heat Pump | Steam |
| Electric Power | % | 62 | 100 | 51 |
| Fuel Gas [MWh]  | % | 100 | - | 83 |
| Overall Energy Consumption (1) | % | 229 | 100 | 276 |
| Overall Energy Cost/tonCO2 (2) | % | 140 | 100 | 169 |

1. Overall Energy Consumption is the sum of the Electric Power and the Fuel Gas power.
2. Estimated price of electric power is 60 €/MW, and estimated price of methane is 30 €/MW.
	1. Conclusions

This study demonstrates that integrating heat pumps into CO₂ capture systems represents an effective solution, particularly for hard-to-abate industries like cement production, where steam availability is limited. The analysis of a plant with a CO₂ capture requirement of 1,600 MTPD highlights the significant advantages of the heat pump configuration over traditional steam-based technology. By leveraging heat pumps, the system achieves an overall energy consumption approximately 70% lower than the steam-based solution, while also avoiding additional CO₂ emissions generated during steam production if powered by renewable sources. In contrast, the traditional approach would require an overdesign from 15% to 30%, depending on solvent energy requirement, to capture these extra emissions, resulting in higher capital (CapEx) and operational (OpEx) costs compared to the heat pump alternative. These findings underscore the energy efficiency and cost-effectiveness of heat pump integration. By eliminating indirect emissions and aligning with electrification goals, this approach provides a sustainable solution for carbon capture systems, contributing to global efforts to reduce greenhouse gas emissions and achieve carbon neutrality.

Nomenclature

CCS – Carbon Capture and Storage

PCCC – Post Combustion Carbon Capture

MTPD – Metric Tons Per Day

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