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Review of Carbon Capture Technology and Its Potential Application to Reduce Emissions in Heavy Equipment Exhausts

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Abstract

Carbon emissions from diesel engines, particularly those from heavy equipment, are a significant greenhouse gas emitter in industries such as construction, mining, and logistics. As global efforts toward decarbonization intensify, carbon capture technologies offer a solution to reduce global emissions. This paper conducts a literature review to explore current carbon capture technologies, including chemical sequestration, physical sequestration, and membrane separation. It evaluates their potential for integration with heavy equipment exhaust systems. Key considerations include system size, energy requirements, maintenance, and operational compatibility. Integration of exhaust heat recovery systems is also assessed as a complementary solution to address the high energy demands of carbon capture in the environment. Technical, economic, and regulatory challenges are discussed, along with potential innovations and use cases that could support future deployments. The findings indicate that although carbon capture is still in its infancy, targeted applications and modular designs supported by policy incentives could enable practical implementation in the near future. This review provides a foundation for future research, pilot projects, and system designs aimed at encouraging the sustainable operation of heavy equipment.

Keywords: Carbon, decarbonization, diesel engines, exhaust heat recovery, heavy equipment

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Emisi karbon dari mesin diesel, khususnya pada alat berat menjadi penghasil gas rumah kaca yang signifikan dalam industri seperti konstruksi, pertambangan, dan logistik. Seiring dengan meningkatnya upaya global menuju dekarbonisasi, teknologi penangkapan karbon menawarkan solusi untuk mengurangi emisi global. Dalam karya ilmiah ini, kami mengkaji berbagai teknologi penangkapan karbon yang ada. Kami mengeksplorasi metode-metode seperti penyerapan kimia, penyerapan fisik, dan pemisahan membran. Kami juga mengevaluasi potensi teknologi-teknologi ini untuk diintegrasikan dengan sistem knalpot alat berat. Pertimbangan utama meliputi ukuran sistem, kebutuhan energi, pemeliharaan, dan kompatibilitas operasional. Integrasi sistem pemulihan panas buang juga dinilai sebagai solusi pelengkap untuk mengatasi permintaan energi yang tinggi dari penangkapan karbon di lingkungan. Tantangan teknis, ekonomi, dan peraturan dibahas bersama dengan inovasi potensial dan kasus penggunaan yang dapat mendukung penerapan di masa mendatang. Temuan menunjukkan bahwa meskipun penangkapan karbon masih dalam tahap awal, aplikasi yang ditargetkan dan desain modular yang didukung oleh insentif kebijakan dapat memungkinkan penerapan praktis dalam waktu dekat. Tinjauan ini memberikan dasar untuk penelitian di masa mendatang, proyek percontohan, dan desain sistem yang ditujukan untuk memungkinkan pengoperasian peralatan berat yang berkelanjutan.

Kata Kunci: Karbon, dekarbonisasi, mesin diesel, pemulihan panas buang, alat berat

INTRODUCTION

Global efforts to achieve net-zero emissions have spurred intensive research and development across various sectors, particularly those that contribute significantly to greenhouse gas (GHG) emissions. Among these sectors, the heavy equipment and construction machinery sector is one of the most challenging to decarbonize [1]. Diesel-powered engines, including excavators, bulldozers, dump trucks, and other off-road vehicles, emit significant amounts of carbon dioxide (CO_2) and particulate matter due to their continuous operation at high loads [2]. While efforts to electrify or hybridize this equipment are underway, the transition is expected to be slow due to technical, economic, and operational constraints [3]. This necessitates interim solutions that can significantly reduce emissions without requiring a complete overhaul of existing units.

One promising solution is the application of carbon capture technology. This method is designed to selectively remove CO_2 from exhaust gases before they are released into the atmosphere. Traditionally, carbon capture has been explored in power plants or industrial facilities. However, advances in materials science, miniaturization, and system integration are now opening the door to adapting carbon capture systems for more dynamic and mobile applications, including those in the heavy equipment sector.

The potential integration of carbon capture systems into the exhaust stream of heavy-duty engines presents both opportunities and complexities. On the one hand, capturing CO_2 at the source can directly reduce emissions without changing the core engine design. On the other hand, significant technical challenges remain, including system size and weight, energy requirements, regeneration or disposal of the capture media, and durability under harsh operating conditions such as vibration, heat, and dust exposure.

The idea of portable carbon capture units, whether based on chemical adsorption (e.g. sodium hydroxide scrubbers), solid adsorbents (e.g. activated carbon, zeolites, or metal-organic frameworks), or membrane separation, is gaining traction as a viable emissions control strategy. Recent studies have demonstrated proof-of-concept prototypes and lab-scale trials, suggesting that this technology could ultimately become part of the emissions reduction toolkit in the off-road and mobile sectors. Although there are existing systematic reviews on carbon capture technologies, they primarily focus on large-scale, stationary applications. Our review, in contrast, addresses a significant gap by providing a focused synthesis of emerging innovations specifically for mobile, small-scale applications like those found in heavy equipment. This makes the novelty and necessity of our work unmistakable.

This study aims to provide a comprehensive overview of current carbon capture technologies and evaluate their potential for application in heavy equipment exhaust systems. This paper analyses various carbon capture technologies, focusing on those with potential for mobile or small-scale applications. It assesses the technical feasibility, integration challenges, and future development directions for implementing such systems in the heavy equipment industry. By bridging the gap between large-scale carbon capture research and real-world mobile applications, this review aims to support ongoing efforts to reduce the carbon footprint in the construction, mining, and logistics sectors in line with global climate goals.

MATERIALS AND METHODS

The methodology employed in this review is based on a systematic literature study focusing on carbon capture technologies and their potential application in heavy equipment exhaust systems. The process involved a comprehensive search and critical selection of academic sources indexed in Scopus within the last ten years, prioritizing peer-reviewed journal articles, conference proceedings, and authoritative reports.

The initial stage consisted of keyword-based searches using combinations such as "carbon capture," "mobile carbon capture," "heavy equipment," "adsorbents," "membranes," "waste heat recovery," and "decarbonization technologies." This search yielded a broad collection of publications that address both fundamental principles and applied research in the field.

Subsequently, the retrieved literature was filtered to ensure relevance to the research objectives. Priority was given to studies that: (i) present recent technological advancements in carbon capture materials and systems; (ii) evaluate economic feasibility, scalability, or regulatory frameworks; and

(iii) discuss opportunities for implementation in mobile or heavy-duty applications. Outdated studies, those that lacked empirical or theoretical depth, or those that fell outside the scope of mobile applications, were excluded.

The final selection of literature was critically analysed to identify prevailing challenges, opportunities for innovation, and emerging trends. By synthesizing insights from these sources, the review aims to provide a comprehensive and up-to-date perspective on the technical, economic, and policy dimensions of carbon capture in heavy equipment applications.

Literature Review

Study selection and screening

Our initial comprehensive search yielded a substantial number of records, specifically [N] records. From this initial pool, we embarked on a systematic process to identify the most relevant studies. Duplicate records were meticulously removed to ensure each study was considered only once. Following this, we proceeded to screen the titles and abstracts of the remaining unique records. This crucial step allowed us to quickly assess the relevance of each study against our predefined inclusion and exclusion criteria.

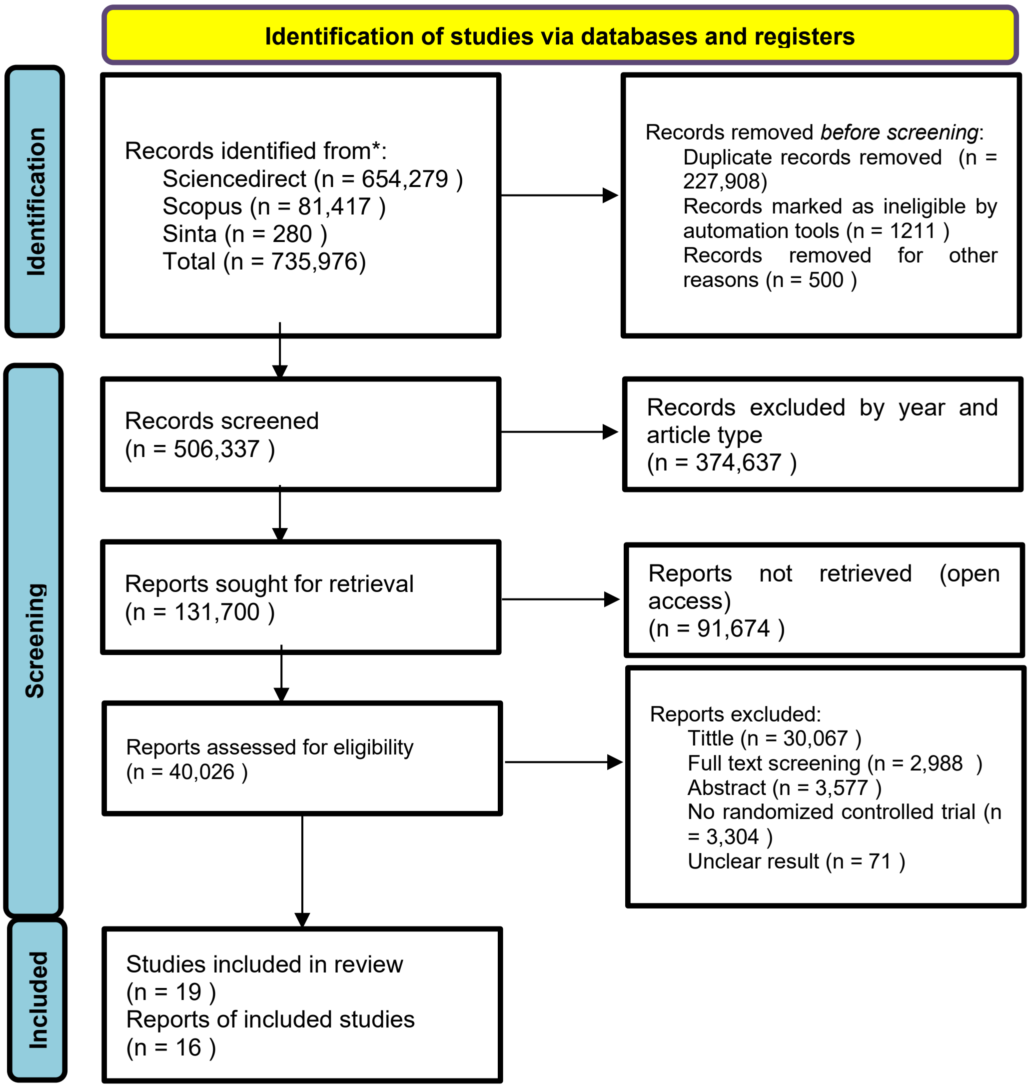

Figure 1. PRISMA Flow Diagram

For those papers that appeared to meet our criteria based on their title and abstract, we then obtained and conducted a full-text review. This in-depth assessment confirmed whether the studies truly aligned with our research scope and provided the necessary information for our synthesis. To visually summarized this entire selection process, we've provided a PRISMA flow diagram in **Figure** 1. This diagram offers a clear, step-by-step overview, illustrating the number of records that were: Identified in the initial search; Screened for relevance; Assessed for eligibility through full-text review; and finally, included in our final synthesis, forming the core of our systematic literature review.

After this comprehensive data extraction, the information was then thematically categorized and synthesized. This systematic organization allowed us to answer our four primary research questions effectively. Where appropriate and beneficial for clarity, we utilized comparative tables and trend analyses to visually represent key insights, highlight commonalities, differences, and emerging patterns across the body of literature

Inclusion and Exclusion Criteria

Our literature search focused narrowly on two areas applied to diesel engines: waste heat recovery (WHR) and carbon capture (CC) technologies. For WHR, we included diverse methods like ORC, thermoelectric generators, and turbo-compounding. For CC, we looked for techniques such as adsorption, absorption, and membrane separation, provided they were tailored explicitly for diesel engine exhaust.

The essential inclusion criterion was original research (e.g., experiments, simulations) published in peer-reviewed sources. We excluded general CC studies not adapted for diesel exhaust's unique properties, purely conceptual papers without empirical proof, and non-peer-reviewed materials like patents or most technical reports. This strict filtering ensured we compiled a high-quality, focused body of evidence detailing proven advancements in the field. To ensure relevance and quality, the following criteria in **Table** 1 were used.

Table 1. Inclusion and Exclusion Criteria

Criteria	Included	Excluded
Publication date	2013–2024	Before 2013
Language	English	Non-English
Technology focus	WHR, CC, or integration	Unrelated to WHR or CC
Type of source	Articles	Patents, theses, technical reports, proceeding
Application context	On-road, off-road, power generation diesel engines	Unrelated to diesel engines

RESULTS AND DISCUSSION

Characteristics Of Exhaust Gas Emissions in Heavy Equipment

Heavy-duty diesel engines are widely used in industries requiring high torque, fuel efficiency, and robust operation. These engines emit a variety of pollutants, including carbon dioxide (CO_2), nitrogen oxides (NO_x), unburned hydrocarbons, and particulate matter. Among these, CO_2 emissions are directly related to the carbon content of the diesel fuel and the combustion process. Under full load conditions, exhaust gas can contain 8 to 12% CO_2 by volume, with temperatures exceeding 300°C and sometimes reaching as high as 600°C. These values indicate that diesel exhaust gas is a viable stream for carbon capture, provided the system can accommodate high temperatures and variable flow rates.

Unlike stationary power sources, heavy equipment operates under variable load conditions, making its emission profile highly dynamic. Exhaust flow rates, pressures, and temperatures frequently fluctuate depending on the duty cycle, load factors, and operating environment. These fluctuations create complexities in maintaining effective and stable CO_2 capture performance.

Spatial and structural limitations further limit the application of capture systems. Any additional modules must be compact, lightweight, and able to withstand environmental stressors such as dust, vibration, and temperature cycling. The system must also be designed for minimal operator intervention and seamless integration with existing engine and exhaust configurations.

Despite these challenges, diesel exhaust's relatively high CO_2 concentration and thermal energy content make it attractive for compact capture solutions. Exhaust heat has the potential to promote sorbent regeneration or improve adsorption efficiency. Furthermore, on-site or onboard capture can reduce emissions at the point of origin, an essential consideration for enclosed or urban work sites.

Understanding these exhaust characteristics is crucial for selecting and designing an appropriate carbon capture system. Precise mapping of parameters such as gas composition, flow rate, and duty cycle provides the basis for technology selection, modelling, and implementation

Overview of carbon capture technology

Various carbon capture [4-8] and separation technologies can be implemented using multiple methodologies, as shown in **Table** 2. Carbon capture technologies include pre-combustion, oxygen combustion, and post-combustion processes. Each of these carbon capture technologies uses different materials and separation methods, depending on the specific needs and demands of the application [9].

Post-combustion capture refers to the process of capturing CO_2 produced by traditional combustion, where air serves as the oxygen provider. As a result, the flue gas contains low concentrations of CO_2 mixed with N_2 and NO Therefore, post-combustion CO_2 reduction is a relatively simple approach to capturing CO_2 produced by standard combustion processes and forms the basis of current CCS infrastructure [10].

Chemical adsorption

A specific approach in Carbon Capture and Adsorption (PCC) technology is chemical adsorption, in which carbon dioxide (CO_2) chemically reacts with solvent molecules [11]. This process is highly efficient for capturing CO_2 from flue gas streams with relatively low concentrations. The chemical adsorption process offers advantages such as high CO_2 selectivity and optimal product gas purity [12].

Commonly used solvents, such as amines, for example, monoethanolamine (MEA) [13]. They have several disadvantages, including high corrosion rates, significant water content in the purified gas, high regeneration energy requirements, typically achieved through elevated temperatures, and considerable energy losses due to evaporation. The use of volatile solvents leads to higher operational costs, both due to condensation in the purified gas stream and solvent refilling. To address these issues, research continues to improve adsorption media by reducing volatility while maintaining high adsorption capacity [14].

One of the main advantages of using chemical adsorption in CO_2 capture is its very low vapor pressure, which reduces concerns about solvent loss due to evaporation [15]. Furthermore, chemical adsorption can be modified by altering its chemical structure, enabling the design of devices with superior characteristics, such as higher CO_2 adsorption capacity, lower toxicity, and improved stability. However, the application of chemical adsorption for CO_2 capture still faces challenges, such as its relatively high viscosity, which can hinder the CO_2 mass transfer rate and affect the overall efficiency of the capture process [16]

Solid adsorption

Adsorption is expected to be the next generation of Carbon Capture, Utilization, and Storage (CCUS) technology, and amine-impregnated solid adsorbents are one promising adsorbent. This technology was first proposed in the 1980s to control CO_2 concentrations in space station habitation chambers, and its application to CCUS began to be considered around 2000 [17]. To date, various materials utilizing amines and porous materials have been developed to enhance CO_2 adsorption performance. A wide variety of solid adsorbent shapes exists, including hollow fibers, sheets, and conventional particles [18].

The adsorbent shape can be tailored to the process operation; for example, in the hollow fiber process, CO_2 is adsorbed by introducing flue gas from outside the hollow fiber bundle, while reaction heat is removed by flowing cold water through the hollow fiber chamber. The material is then heated directly by pouring hot water to desorb CO_2 [19].

Cryogenic distillation

Cryogenic carbon capture (CCC) is a carbon capture technology that offers significant energy and cost advantages compared to alternatives. This process is a post-combustion technology that cools CO_2-containing flue gases to the de-sublimation temperature (-100 to -135°C), separates the solid CO_2 from the light gases in the flue gas, uses the cooled product to cool the incoming gas in a recuperative heat exchanger, compresses the solid/liquid CO_2 to a final pressure (100-200 atm) read for capture or storage, and produces a compressed CO_2 stream separated from the atmospheric pressure light gas stream [20].

The overall energy and economic costs appear to be at least 30% lower than most competing processes involving air separation units (ASUs), solvents, or similar technologies. In addition, the CCC process enjoys several additional benefits, including (a) being a minimally invasive adjunct technology, (b) providing highly efficient removal of most pollutants (Hg, SOx, NO_2, HCl, etc.), (c) enabling energy storage capacity, and (d) potential water savings [21].

Electrochemical processes

Electrochemical carbon capture and concentration (eCCC) offers a promising alternative to thermochemical processes because it can overcome the temperature limitations of capture and release. [22]. We are conducting a thorough examination of electrochemical carbon capture (eCCC), specifically exploring its use to lower pollution from vehicles and machinery. We'll start by looking at the original eCCC ideas from the 1960s and 1970s and then move forward to cover recent breakthroughs. For every technology discussed, we will highlight its successes, identify current obstacles, and suggest directions for future development [23,24].

Table 2. Previous Research Related to Carbon Capture

Technology	Mechanism	Advantages	Disadvantages
Chemical Adsorption [4]	1. CO_2 Diffusion to the Adsorbent Surface 2. Adsorption on Active Sites 3. Chemical Bond Formation 4. Chemical Reaction (Optional) 5. CO_2 Desorption and Adsorbent Regeneration	1. **High CO_2 Capture Capacity**: The formation of chemical bonds allows for the absorption of significant amounts of CO_2. 2. **High Selectivity**: Chemical adsorbents can be designed to target CO_2 among other gases specifically.	**1. High Regeneration Energy:** Desorption processes that require the breaking of strong chemical bonds require more energy than physical adsorption. 2. **Adsorbent Degradation Potential:** Chemical adsorbents can degrade over time due to side reactions or extreme operating conditions.
Solid Absorption [5]	1. Adsorption 2. Desorption (Regeneration) 3. CO_2 Collection 4. Repeated Cycle	1. **Operational Flexibility:** Solid-state adsorption technology can be operated under a wide range of temperature and pressure conditions. 2. **Wide Range of Material Options:** Solid-state materials that can be used as adsorbents include activated carbon, zeolites, alumina, silica, MOFs (Metal-Organic Frameworks), and porous polymers.	1. **Adsorption and Desorption Kinetics**: The adsorption and desorption processes in some solid materials may be relatively slow, which can limit the overall carbon capture rate. 2. **Adsorbent Material Cost:** Some highly effective adsorbent materials, such as MOFs, can have high production costs. 3. **Development and Scalability:** Some solid adsorption technologies are still in the development stage.
Membrane Separation [6]	1. Gas Feed 2. Membrane Contact 3. Selective Permeation 4. Flow Splitting: After passing through the membrane, the gas stream will split into two: a. Permeate b. Retentate (or Reject) 5. CO_2 Collection	1. **Lower Energy Consumption**: The process is less physical and does not require intensive solvent heating for regeneration. 2. Simpler Design and Operation 3. **Smaller Footprint**: Membrane modules are typically more compact and have a smaller footprint than large absorption devices, making them suitable for space-constrained applications.	1. **Membrane Susceptibility to Degradation**: Membrane materials can degrade due to contaminants in the exhaust gas (such as particulates, SOx, and NOx). 2. **High Membrane Material Cost**: The development and production of high-performance membrane materials (good permeability and selectivity, as well as long-lasting durability) is still relatively expensive. 3. **Sensitivity to Operating Conditions**: Changes in temperature and pressure can cause fluctuations in capture efficiency.
Cryogenic Distillation [7]	1. Gas Pretreatment 2. Gradual Cooling 3. CO_2 Separation 4. CO_2 Collection and Purification 5. Reheating of Waste Gas	**High CO_2 Purity**: This process can produce CO_2 with a very high degree of purity.	1. **High Energy Consumption**: Cooling to cryogenic temperatures requires a significant amount of energy, resulting in high operational costs. 2. **Inefficient for Low CO_2 Concentrations**: This technology is generally more effective for flue gases with relatively high CO_2 concentrations.
Electrochemical Process [8]	1. CO_2 Absorption 2. Carbonate/Bicarbonate Ion Formation 3. Direct CO_2 Reduction 4. Metal-CO_2 Compound Formation 5. Electrode Regeneration and CO_2 Release 6. CO_2 Collection and Utilisation	1. **Potential for High Energy Efficiency**: Some electrochemical system designs have the potential for higher energy efficiency. 2. **Tunable Selectivity**: With proper electrode material selection and operating conditions, selectivity to CO_2 can be increased, reducing the need for further purification. 3. **Cleaner and Safer Operation**: Electrochemical processes can avoid the use of hazardous chemical solvents and produce less waste.	1. **Electrode and Electrolyte Material Challenges**: It is challenging to develop electrode and electrolyte materials that are stable, efficient, and durable under extreme operating conditions. 2. **High Initial Costs:** The initial development and implementation costs of electrochemical technology may be higher. 3. **Energy Requirements for Operation:** Electrochemical processes still require electrical energy for their operation.

Potential for integration with heavy equipment

Integrating carbon capture systems into heavy equipment poses unique challenges but also opens up innovative opportunities. These machines, widely used in sectors such as construction, mining, agriculture, and transportation, operate under dynamic loads, in harsh environments, and with limited internal space. Therefore, any retrofit carbon capture solution must be compact, durable, energy-efficient, and minimally disruptive to the machine's core functions. To address these constraints, researchers and engineers are exploring several promising approaches beyond the traditional large-scale systems. Instead of relying on bulky amine scrubbers, next-generation sorbents offer a more compact solution. Metal-organic frameworks (MOFs) and zeolites are porous materials with a high surface area that can selectively capture CO_2 at lower temperatures and pressures. These materials can be integrated into a compact reactor design that fits within the limited space of a heavy equipment chassis. Their high CO_2 capacity and regenerability make them suitable for mobile applications. Membranes can offer a continuous and passive method for CO_2 separation. Polymeric membranes and mixed-matrix membranes can be designed to permeate CO_2 while rejecting other exhaust gases selectively. A modular, stacked membrane system could be placed in the exhaust stream, allowing for CO_2 separation without the need for significant energy input or complex chemical processes. This approach is highly scalable and has a small footprint, making it ideal for mobile retrofits. eCCC represents a promising and novel solution. This method uses an electrochemical cell to drive the CO_2 capture process, often regenerating the capture medium in situ. An eCCC system can be designed to be highly modular and responsive to the intermittent operation of heavy equipment. For example, a system could use a specialized electrolyte that absorbs CO_2 on one electrode and releases it in a concentrated stream at the other. The machine's own electrical system can power the system, making it an energy-efficient and self-contained solution. The CO_2 captured can then be stored in a pressurized tank or used for on-board applications

Challenges in implementing waste heat recovery and carbon capture in diesel engines

The implementation of Waste Heat Recovery (WHR) and Carbon Capture (CC) on diesel engines presents a triad of significant hurdles. These challenges can be broadly classified as:

1. *Technical and Engineering Challenges*.

These issues relate directly to the physical integration and performance of the systems on the engine. The data are listed in **Table** 3.

Table 3. Technical and engineering challenges

Waste Heat Recovery Challenge	Carbon Capture Challenge	Combined Challenge
Transient Operation: Diesel engine heat output, especially in vehicles, is constantly changing. WHR systems (like ORC) struggle to maintain optimal efficiency and quick response under highly dynamic load cycles. [24]	Exhaust Characteristics: Diesel exhaust gas has a relatively low CO_2 concentration and contains pollutants (NOx, SOx, Particulate Matter) that can degrade or foul capture materials (solvents, sorbents, membranes) [19].	System Integration and Weight: Adding large components like heat exchangers, turbines, pumps (for WHR), or capture reactors, storage tanks, and compressors (for CC) significantly increases engine back pressure and vehicle weight and requires substantial packaging space [25].
Material Degradation: High exhaust gas temperatures and corrosive components require expensive, high-performance materials for heat exchangers and working fluids, leading to high maintenance and material costs [26].	Energy Penalty: The capture process itself is highly energy-intensive, requiring additional power or heat, which partially negates the efficiency gains from WHR or increases overall fuel consumption [27].	Impact on Durability: Complex auxiliary systems increase the potential points of failure and require robust control strategies to operate reliably over the engine's lifespan [28].
Low-Grade Heat Utilisation: Much of the waste heat from sources like the coolant is at a low temperature, making its conversion into useful power inefficient [29].	CO_2 Storage/Disposal: On mobile applications, a practical, safe, and compact solution for on-board CO_2 storage is currently non-existent [30].	

2. *Economic and Financial Challenges*.

The primary obstacles for end-users adopting these technologies are financial, specifically related to cost, investment, and return on investment (ROI). Both Waste Heat Recovery (WHR) and Carbon Capture (CC) demand a high Capital Expenditure (CAPEX) for specialized equipment like ORC turbines, CO_2 capture modules, and unique heat exchangers. This significant upfront cost makes them a difficult sell for industries like transportation and power generation, which are very sensitive to price [31]. Consequently, the time it takes to recoup the investment through fuel savings (WHR) or selling carbon credits (CC) often results in a long payback period that isn't commercially appealing unless strong regulations are in place. Furthermore, Carbon Capture increases Operating Expenditure (OPEX) due to the need for costly sorbents or solvents, the energy required for their reuse, and higher maintenance [32]. Finally, a lack of regulatory incentives like carbon taxes or subsidies means these systems cannot compete economically with traditional diesel operation in many markets [33].

3. *Operational and Logistical Challenges*

Integrating these technologies is often logistically challenging because of their size, making it hard or impossible to retrofit them into existing engine or vehicle designs, particularly for heavy-duty trucks and smaller generators. The added system complexity, such as handling organic working fluids in WHR or managing chemical solvents and high-pressure gas in CC, demands specialized training for maintenance staff and operators, which increases the operational burden [34]. Furthermore, both WHR and CC introduce new safety concerns [35] due to the presence of high-pressure components and the potential use of toxic or flammable working fluids. Finally, the necessary infrastructure is nonexistent for the transport and permanent storage of captured CO_2, especially from decentralized sources like trucks, creating a major logistical hurdle for the entire value chain.

CONCLUSION

Integrating carbon capture technology into heavy equipment exhaust systems is a new and promising approach to reducing emissions in difficult-to-decarbonize sectors such as construction, mining, and agriculture. While carbon capture has traditionally been applied to stationary industrial sources, recent advances in materials science, system miniaturization, and process integration have begun to open the door to mobile applications. This paper has reviewed the main types of carbon capture technologies, chemical adsorption, physical adsorption, and membrane separation, and explored their feasibility for use in heavy-duty diesel equipment. Among these, chemical adsorption systems using alkaline or amine solutions currently hold the most tremendous potential but require careful consideration of energy demand, corrosion, and byproduct handling. Physical adsorption and membrane technologies offer more compact solutions but face technical challenges related to durability, selectivity, and environmental tolerance.

The potential to integrate exhaust heat recovery with carbon capture processes offers significant opportunities to overcome energy barriers, particularly given the high exhaust temperatures of diesel engines. However, system design must account for operational variability, space constraints, and maintenance limitations common to heavy equipment use cases. As we advance, the use of renewable fuels or hybrid powertrains holds significant promise. Continued research, collaboration between industry and academia, and policy support will be crucial to accelerate the development and deployment of these systems.

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