

# Membrane Gas Separation for Post-Combustion CO<sub>2</sub> Capture and Utilization in Hybrid Energy Systems

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The urgent need to mitigate greenhouse gas (GHG) emissions has placed the energy sector at the center of global decarbonization efforts, as fossil fuel combustion accounts for a major share of anthropogenic CO<sub>2</sub> emissions. Post-combustion carbon capture represents a key strategy for reducing emissions from existing power plants, while enabling the valorization of captured CO<sub>2</sub> through Carbon Capture and Utilization (CCU) pathways. Among the available capture technologies, membrane gas separation has attracted increasing interest due to its compact design, low energy requirements, operational simplicity, and potential for modular deployment (Gkotsis et al., 2023).

This study focuses on the investigation of a membrane-based gas separation process for post-combustion CO<sub>2</sub> capture from flue gas streams. The proposed system aims to selectively separate CO<sub>2</sub> from nitrogen-rich exhaust gases of coal-fired power plants and produce a CO<sub>2</sub>-enriched stream suitable for downstream utilization. In particular, the captured CO<sub>2</sub> is intended to be integrated with a biological methanation unit, where it can be converted into biomethane using renewable hydrogen, contributing to hybrid energy storage and sustainable fuel production.

Polyimide (PI) hollow fiber membranes were selected as the separation medium due to their high CO<sub>2</sub>/N<sub>2</sub> selectivity, chemical stability, and suitability for industrial-scale applications (Xu J. et al. 2018). The investigation includes both laboratory-scale and pilot-scale membrane configurations. Initially, a single-stage membrane separation unit was evaluated using synthetic CO<sub>2</sub>/N<sub>2</sub> gas mixtures that simulate typical post-combustion flue gas compositions. The experimental setup comprises mass flow controllers, pressure regulation devices, gas analyzers, and a programmable control system, allowing precise control of operating parameters such as feed composition, pressure, and flow rate.

Based on the findings of the single-stage configuration, a pilot-scale two-stage membrane separation system was designed and constructed. The multi-stage concept involves the serial and parallel arrangement of multiple identical membrane modules, combined with intermediate compression and selective recirculation of gas streams. This configuration is intended to enhance CO<sub>2</sub> enrichment while maintaining operational flexibility. The system is fully instrumented and controlled via a programmable logic controller (PLC), enabling stable operation and continuous monitoring of process variables.

The membrane separation unit is designed with scalability in mind and was intended for installation at the Agios Dimitrios V Power Plant of the Public Power Corporation (PPC) in Ptolemaida, Greece. Under real operating conditions, the system will treat actual flue gas streams and deliver a CO<sub>2</sub>-rich product suitable for utilization. The captured CO<sub>2</sub> can be combined with hydrogen produced via water electrolysis powered by renewable energy

sources, enabling the production of biomethane through biological methanation. The produced biomethane can be injected into the natural gas grid or used to meet the energy demands of remote and non-interconnected areas.

Overall, this work demonstrates the potential of membrane gas separation as an effective post-combustion CO<sub>2</sub> capture technology that can be integrated with CCU applications. The proposed approach supports emission reduction, renewable energy storage, and decentralized energy systems, contributing to the broader goals of climate neutrality and sustainable energy transition.

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### **References**

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