Multi-Objective Optimization of a Wind-Integrated Carbon Capture and Conversion Process for Liquid Synthetic Methane Production

Introduction

The increasing concentration of atmospheric carbon dioxide (CO_2) and the growing urgency to achieve global decarbonization targets have accelerated interest in carbon capture and utilization (CCU) technologies [1]. Among the various CCU pathways, the conversion of captured CO_2 into synthetic fuels has attracted significant attention because it reduces greenhouse gas emissions and provides valuable energy carriers. Synthetic methane offers several advantages, including compatibility with existing natural gas infrastructure, ease of storage and transportation, and potential for large-scale deployment [2]. The integration of renewable energy with CCU systems has emerged as a promising pathway for producing low-carbon fuels [3]. Wind energy can provide renewable electricity for water electrolysis, enabling the production of green hydrogen (H_2), which subsequently reacts with captured CO_2 through the Sabatier reaction to produce synthetic methane [4]. Several studies have investigated different aspects of renewable methane production, including carbon capture, H_2 generation, methanation, and liquefaction processes [5, 6]. Al-Breiki et al. [7] compared liquefied H_2 and liquefied renewable methane pathways and demonstrated that liquefied renewable methane offers lower production energy requirements, reduced boil-off losses, and compatibility with existing liquefied natural gas infrastructure. Safari et al. [8] developed a wind-based power-to-gas system incorporating a wind turbine, proton exchange membrane (PEM) electrolyzer, and Sabatier methanation unit, reporting overall energy and exergy efficiencies of 44% and 45%, respectively.

At present, the production of synthetic methane remains relatively expensive, with reported costs ranging from approximately 15 to 180 $/million Btu [3, 9-12]. Reported costs vary widely depending on electricity prices, CO_2 source, and system configuration. More detailed analyses show that costs can range from approximately 16 to 35 $/million Btu for optimized systems, 43 to 52 $/million Btu for integrated supply chains, and increase up to 67 to 179 $/million Btu when direct air capture is employed [11-13]. Future projections suggest a gradual decline, with costs expected to fall to around 23-110 $/million Btu by 2030 and 15-60 $/million Btu by 2050, particularly in regions with access to low-cost renewable electricity and improved system efficiencies [14]. In addition, compatibility with existing liquefied natural gas (LNG) infrastructure strengthens the potential of synthetic methane as a practical energy carrier, particularly in remote regions [4]. These studies demonstrate the technical feasibility of renewable methane production and highlight the importance of process integration, thermal management, and system optimization for improving overall performance.

Despite these advances, significant challenges remain regarding process integration, energy efficiency, methane liquefaction, and economic feasibility. Most previous studies have focused on individual subsystems or partially integrated configurations, while limited attention has been devoted to the simultaneous integration of carbon capture, H_2 production, methanation, and methane liquefaction within a unified framework. Furthermore, methane liquefaction remains one of the most energy-intensive stages of the overall process and has received comparatively less attention than H_2 production and methanation [15]. In addition, the combined application of pinch analysis, exergy assessment, machine learning techniques, and multi-objective optimization for liquid synthetic methane production has not been comprehensively investigated.

To address these gaps, this study proposes a wind-integrated carbon capture and conversion system for liquid synthetic methane production. The proposed configuration combines a monoethanolamine (MEA)-based CO_2 capture unit, a proton exchange membrane (PEM) electrolyzer for green H_2 production, a catalytic methanation reactor, and a mixed-refrigerant (MR) liquefaction cycle. Aspen HYSYS and MATLAB are employed for process simulation and performance evaluation. Pinch, exergy, and techno-economic analyses are conducted to assess system performance, while machine learning models and genetic algorithm-based multi-objective optimization are utilized to identify optimal operating conditions. The objective is to simultaneously maximize exergy efficiency and minimize the levelized fuel cost while providing a sustainable pathway for large-scale renewable methane production and carbon utilization.

Methodology

This study develops an integrated wind-powered carbon capture and conversion system for liquid synthetic methane production. As illustrated in Figure 1, the proposed configuration consists of four major subsystems, including CO_2 capture, H_2 production, methane synthesis, and methane liquefaction. Renewable electricity generated by wind turbines serves as the primary energy source for the entire process. CO_2 is captured from flue gas streams using an MEA-based post-combustion capture process. The captured CO_2 is subsequently compressed and delivered to the methanation unit. H_2 is produced through a PEM electrolyzer powered by renewable wind electricity. The generated H_2 reacts with captured CO_2 through the Sabatier reaction to produce methane and water. Due to the highly exothermic nature of the methanation process, heat recovery opportunities are incorporated into the system to improve overall energy utilization. The methane product is then purified and liquefied using an MR liquefaction cycle to generate export-ready liquid synthetic methane suitable for long-distance transportation and storage. The integrated system is modeled using Aspen HYSYS software coupled with MATLAB-based m-file codes. Aspen HYSYS package is employed for process simulation, thermodynamic calculations, reaction modeling, and equipment performance evaluation, while MATLAB programming is used for data processing, machine learning model development, and optimization studies.

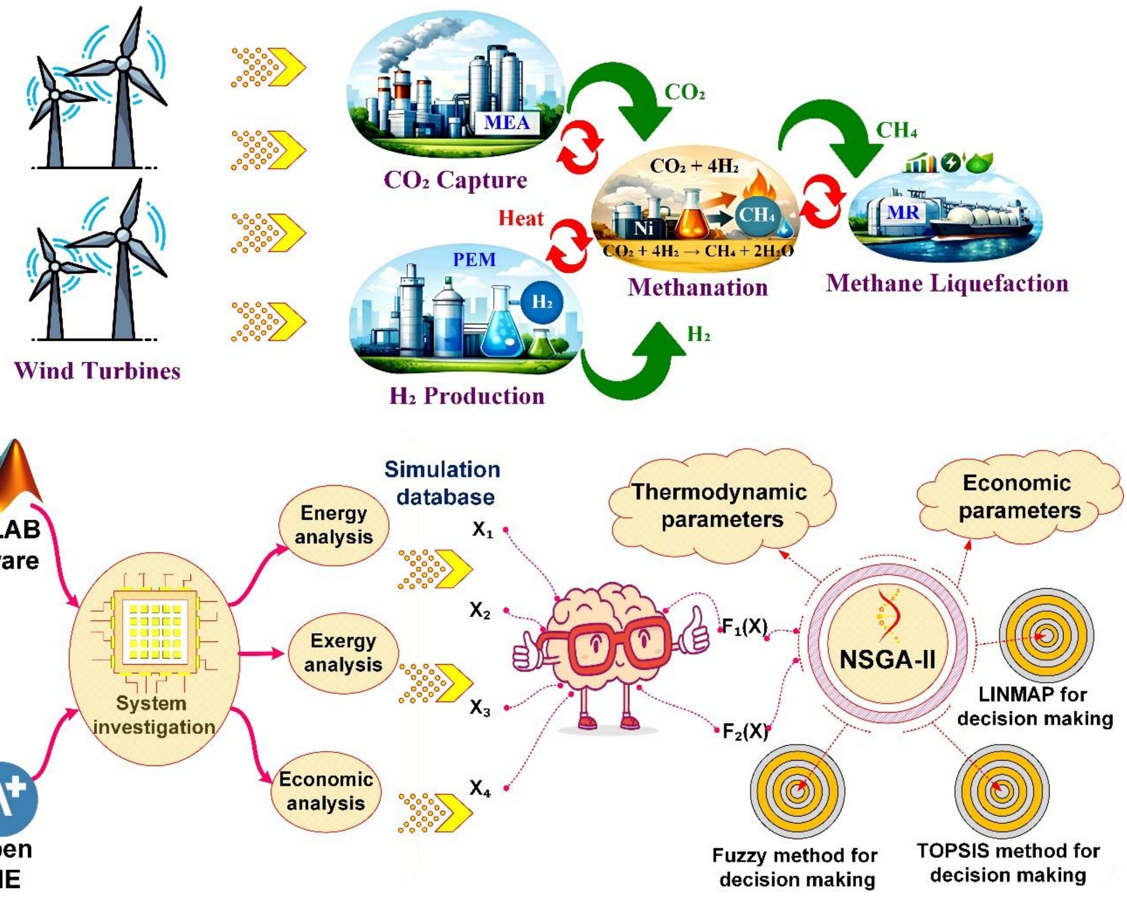

Figure 1. Integrated process configuration and machine learning-based multi-objective optimization framework for liquid synthetic methane production.

To improve system performance, pinch analysis is conducted to identify heat recovery opportunities and minimize external utility requirements. Exergy analysis is performed to evaluate thermodynamic inefficiencies and identify major sources of irreversibility within the integrated system. In addition, techno-economic analysis is conducted to estimate capital investment, operating costs, annualized system cost, and levelized fuel cost. A comprehensive optimization framework is developed to identify the optimal operating conditions of the integrated system. Sensitivity analysis is performed to determine the most influential process variables affecting thermodynamic and economic performance. A large simulation database is subsequently generated using Aspen HYSYS software and MATLAB programming. The generated dataset is used to train machine learning models capable of predicting system performance under different operating conditions. The mathematical relationships obtained from the machine learning models are coupled with a genetic algorithm-based multi-objective optimization approach. The optimization simultaneously maximizes exergy efficiency and minimizes levelized fuel cost. The non-dominated sorting genetic algorithm II (NSGA-II) is employed to generate Pareto-optimal solutions. Subsequently, TOPSIS, LINMAP, and fuzzy decision-making methods are applied to determine the most appropriate operating point from the Pareto frontier.

Conclusions

An integrated wind-powered carbon capture and conversion system for the production of liquid synthetic methane has been proposed and developed. The configuration combines MEA-based CO_2 capture, PEM electrolysis, catalytic methanation, and MR-based methane liquefaction within a unified framework. The proposed system enables the conversion of renewable electricity and captured CO_2 into a storable, transportable low-carbon fuel while utilizing existing natural gas infrastructure.

A comprehensive assessment framework incorporating process simulation, pinch analysis, exergy analysis, techno-economic evaluation, machine learning modeling, and multi-objective optimization is established. The integration of these approaches provides a systematic methodology for identifying the most influential operating parameters and improving overall system performance. The proposed framework is expected to enhance process integration, improve heat recovery opportunities, and support the identification of operating conditions that reduce energy consumption and fuel production costs. Particular attention is required for the PEM electrolyzer and CO_2 capture units, which are anticipated to represent major contributors to both capital investment and operating costs. The outcomes of this study will provide valuable insights into the design, optimization, and large-scale deployment of renewable methane production systems, particularly in regions with abundant wind resources. Future work will focus on uncertainty analysis, advanced exergoeconomic assessment, and life cycle assessment (LCA) of the proposed configuration to further improve its thermodynamic, economic, and environmental performance.

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