

Quantitative modeling framework for assessing the environmental- economic- health impacts of carbon capture, utilization, and storage systems

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<https://hdl.handle.net/2324/7363868>

出版情報 : Kyushu University, 2024, 博士 (学術) , 課程博士
バージョン :

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ABSTRACT

Global warming and air pollution are critical environmental and public health challenges, intensified by rapid population growth and industrial activities. The increasing energy demand, primarily met by fossil fuels, not only drives greenhouse gas (GHG) emissions but also worsens air quality. Carbon capture utilization and storage (CCUS) technologies have emerged as a vital strategy to reduce CO₂ emissions while meeting energy needs. Although developed nations have made significant progress in deploying CCUS technology, challenges such as financial limitations, insufficient infrastructure, and political instability hinder its widespread adoption in developing countries. Implementing CCUS and exploring regional carbon capture collaborations could offer pathways toward environmental sustainability and economic growth.

Within the Middle East and North Africa (MENA) region, the Iraqi community faces a significantly elevated rate of premature mortality due to air pollution. Iraq's failure to ratify the Paris Agreement reflects a limited commitment to emissions reduction efforts. Iraq heavily depends on fossil fuels to generate electricity, a reliance that has intensified in recent years due to population expansion and escalating electricity demand. In recent times, this country has experienced a decline in air quality, which is attributed to a rise in the number of electric power plants, particularly those utilizing fossil fuels. Iraq's sustainable sector development plan prioritizes the reduction of GHG emissions from the oil and gas industry. Implementing CCUS is considered one of the specific technologies and practices outlined in Iraq's Nationally Determined Contributions (INDC).

This dissertation addresses the implementation of CCUS in Iraq's power sector to mitigate environmental and health impacts while fostering economic benefits. To this aim, a comprehensive modeling framework, which includes four main sub-models, is developed. The first sub-model uses the Life cycle assessment (LCA) methodology to examine the environmental impacts of a natural gas combined cycle power plant with post-combustion carbon capture (NGCC-CCS) in Iraq, taking into account two different design scenarios. In the first scenario (retrofit), the carbon capture unit is considered as an end pipe technology that can be linked to an existing power plant. The second scenario considers a grassroots design, in which a new power plant equipped with a carbon capture unit needs to be constructed. The second sub-model analyzes the impact of uncertain oil and carbon market prices on the economic value of CCUS projects, which contributes to appropriate investment and future policy decisions. It explores the potential trade-offs between available CO₂ quantities for trading or injection for enhanced oil recovery in three different oil fields of Rumaila (giant), Nassriya (medium), and Noor (small) in the southern Basra Province of Iraq. The third sub-model assesses the multiple environmental, health, and economic benefits from implementing

carbon capture technology in the power sector of Basra province, Iraq. It first quantifies the captured CO₂ emissions and the equivalent avoided PM_{2.5} emissions resulting from the use of carbon capture units in existing power plants in Basra. Then, the impact of avoided PM_{2.5} exposure on public health is evaluated by applying a dynamic dispersion model and the health impact assessment method across the districts where the power plants are located. Finally, the economic value of avoided health burdens is estimated by employing the value of statistical life (VSL) and the cost of illness (COI) approaches. The fourth sub-model investigates the techno-economic assessment of the utilization of the CCUS in Power-to-X (PtX) applications by integrating solar-powered hydrogen electrolysis with carbon capture and Fischer-Tropsch (FT) synthesis processes for e-fuel production in Basra, Iraq. It uses the detailed simulation of E-fuel production along with the system cost analysis.

The findings of the LCA sub-models indicate that retrofitting existing natural gas combined cycle power plants with post-combustion carbon capture can achieve a 28% reduction in Global Warming Potentials (GWPs), although it results in a 14% increase in Particulate Matter Formation Potential (PMFP) and a 17% increase in Acidification Potential (AP) compared to a grassroots scenario. The economic analysis of the CCUS-enhanced oil recovery (EOR) projects demonstrates that the project's profitability is significantly influenced by fluctuations in oil and carbon market prices, highlighting the necessity for a higher carbon price to mitigate financial challenges due to declining oil prices. The medium-sized oil fields consistently prioritize carbon injection for EOR, while smaller and larger fields adapt their strategies based on prevailing market dynamics. Therefore, CCUS could be a viable solution for Iraqi power plants, particularly those in the southern region, given a realistic demand for EOR of 4.59, 1.04, and 0.071 million tonne CO₂ per year for the giant, medium, and small fields, respectively. The results of the multiple co-benefits assessment reveal that, implementing new carbon capture units could result in the capture of approximately 7.697 million tons of CO₂ annually, alongside a reduction of 2,299 tons of PM_{2.5} emissions in Basra province. This leads to the avoidance of 1,328 premature deaths and 217 hospital admissions, yielding annual economic savings of \$1,846 million from avoided health burdens and the creation of 29,607 green jobs in Basra Province. Finally, the techno-economic assessment of a Power-to-X (PtX) system designed to be located near the Hartha power plant shows significant potential, producing 2.44 tonnes of C₁₂-C₂₀ hydrocarbons and 3.36 tonnes of C₂₁-C₄₀ heavy oils annually. A cash flow analysis indicates that an e-fuel market price of \$10 per liter is needed to achieve a positive cash flow within 15 years, with a \$200 per tonne carbon tax improving the project's economic feasibility.

Overall, the results underscore the multifaceted benefits of CCUS technology, emphasizing its potential to enhance environmental sustainability, public health, and economic growth in Iraq. By synthesizing the findings of the developed modeling framework, this dissertation provides a detailed evaluation of the environmental, economic, and health benefits

of CCUS technology in the power sector. The research contributes to the global discourse on carbon management and presents actionable insights for policymakers aiming to balance carbon reduction with economic growth.

Keywords: Carbon capture, Economic Feasibility, Co-benefits, Enhanced oil recovery, Life cycle assessment, Power-to-X , E-fuel production