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A Techno-Economical Assessment for Decentralized Autonomous Green Methanol Production

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Abstract— **This study presents a techno-economic feasibility study of a decentralized autonomous green methanol plant fully powered by renewable energy. Designed for deployment in remote, off-grid regions, the concept integrated solar photovoltaic generation, solid sorbent-based direct air capture of carbon dioxide, sorbent-based atmospheric water harvesting with indirect carbon dioxide hydrogenation. A multi-criteria decision analysis framework was applied for selection of subsystems based on autonomy, robustness, integration complexity, and energy efficiency. A comprehensive energy and mass balance revealed a specific energy consumption of 2119 kilojoules per mole, highlighting the energy-intensive nature of the process. Despite this, the plant remained competitive due to its modularity and site-specific optimization. Location analysis using a system modelling tool identified Duqm, Oman, as the most favourable site, offering consistent solar irradiance and low energy costs. A solar-only configuration is selected to reduce system complexity compared to hybrid solar-wind setups. A custom simulation framework incorporating model predictive control demonstrated uninterrupted operation under variable solar conditions, even with forecast uncertainty. Under these conditions, the plant achieved a levelized cost of energy of 174.30 dollars per megawatt-hour, which aligns with projected e-fuel costs for 2030. These findings confirmed the technical viability and economic competitiveness of autonomous decentralized methanol production, offering a scalable solution for sustainable fuel generation in remote and decarbonizing regions.**

Keywords: autonomy, decentralized, renewable energy, techno-economic analysis, e-fuels

I. INTRODUCTION

The global transition toward sustainable energy systems has intensified the search for innovative solutions that address decarbonization, energy access, and operational resilience. One promising approach is the deployment of decentralized autonomous chemical production facilities, particularly in remote areas with no connectivity to a power grid. This research explores the feasibility of an autonomous methanol plant powered by renewable energy sources in such remote areas.

Methanol is a versatile chemical and it offers a pathway to carbon-neutral industry with applications ranging from fuel to feedstock, and its synthesis from renewable inputs CO_2 and H_2O [1][2]. Decentralized and autonomous operation offers distinct advantages for methanol production. By eliminating the need for grid connectivity, decentralized plants avoid transportation losses, infrastructure costs, and land-use conflicts in populated areas. Autonomy further enhances the concept by reducing labour requirements and improving safety, enabling continuous operation with minimal human oversight [3]. Together, these principles enable the plant to function as a self-sufficient unit, capable of producing sustainable fuel in locations where conventional infrastructure is unavailable or impractical. The integration of predictive control and robust system design ensures stable operation, which is essential for achieving reliability and scalability in off-grid environments. Autonomous operation, defined in this work as the plant's ability to self-operate using locally available renewable energy without human intervention. While digitalization is essential for autonomy, its costs were excluded from the economic scope of this study.

The concept integrates four key subsystems: solar PV generation, solid sorbent Direct Air Capture (DAC) unit, sorbent-based Atmospheric Water Harvesting (AWH) unit, and indirect CO_2 hydrogenation. These components were selected through a structured Multi-Criteria Decision Analysis (MCDA) process, prioritizing autonomy, robustness, and integration simplicity. The plant's performance was evaluated using energy and mass balance modelling, techno-economic simulations, and a custom control framework based on Model Predictive Control (MPC).

Three locations, Geraldton (Australia), Lüderitz (Namibia), and Duqm (Oman), were assessed for deployment feasibility. Duqm emerged as the most suitable due to its consistent seasonal solar irradiance and favourable cost structure. The study aimed to answer the central research question: *What is the techno-economic feasibility of a decentralized autonomous green methanol plant powered by renewable energy sources?* By addressing this question, the research can contribute to the advancement of autonomous renewable chemical production and offers a blueprint for scalable deployment in remote regions.

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II. METHODOLOGY

A. Multi-Criteria Decision Analysis (MCDA)

A MCDA framework was used to select the most suitable technologies for each subsystem of the plant. The concept was divided into four core functions: energy supply, CO_2 capture, H_2O capture, and reaction method. Each function was evaluated against criteria such as autonomy, integration complexity, energy efficiency, robustness, scalability, and location adaptability. Criteria weighting was performed using the Analytic Hierarchy Process (AHP), supported by expert elicitation and literature review. Technologies with too low maturity or out of scope characteristics were excluded prior to scoring.

B. Energy and Mass Balance

Following subsystem selection, an energy and mass balance was constructed to define the system's input-output relationships. A steady-state model was developed using conservation principles and literature-based component data. The balance includes stoichiometric ratios, enthalpy flows, and component efficiencies. This model serves as the foundation for subsequent simulation and optimization.

C. Future Energy System Modelling (FESM)

To explore location-specific feasibility, the Shell in-house Future Energy System Modelling (FESM) tool was used. This linear programming tool simulates system behaviour under cost-minimization constraints, using renewable energy profiles and component data. While FESM does not fully represent the concept plant, it provides directional insights into system sizing, methanol output and cost structures. Three candidate locations: Geraldton (Australia), Lüderitz (Namibia), and Duqm (Oman), were evaluated.

D. Modelling and Simulation

A custom simulation framework was developed in SciLab to evaluate autonomous operation under realistic conditions. The model incorporates all subsystems and simulates hourly plant behaviour over a full year. A base case was constructed using the energy and mass balance, followed by configuration optimization to create a system setup that meets the monthly methanol production targets with the lowest Levelized Cost of Energy (LCOE). MPC strategies were implemented to manage energy allocation under variable solar conditions and weather forecast uncertainty.

III. RESULTS & DISCUSSION

This section presents the outcomes of the techno-economic assessment of the autonomous, decentralized green methanol plant. Each subsystem followed to a methodological step, providing insights into the technical feasibility, economic viability, and operational performance of the whole concept.

A. Multi-Criteria Decision Analysis (MCDA)

The MCDA framework guided the selection of technologies for each subsystem based on autonomy, integration complexity, energy efficiency, robustness, scalability, and location adaptability. The analysis revealed that:

- Solar PV was selected as the primary energy source due to its maturity, modularity, and compatibility with autonomous operation. While hybrid solar-wind systems scored slightly higher, the added complexity was deemed undesirable for autonomous deployment.
- Solid sorbent-based DAC was chosen for CO_2 capture. Despite electrochemical DAC scoring highest, its low maturity excluded it from the base case. Solid sorbents offer stable performance across climates and support modular deployment [5].
- Sorbent-based AWH was selected for water harvesting, outperforming dew plates and fog nets in adaptability and compatibility with solar-driven desorption [6][7][8].
- Indirect CO_2 hydrogenation was selected as the reaction method due to its high conversion efficiency (≈80%), operational simplicity, and absence of water in the end-product [9].

These selections formed the foundation of the concept plant, designed for modularity, robustness, and autonomous operation.

B. Energy & Mass Balance

A comprehensive energy and mass balance was constructed to quantify the system's input-output relationships. The analysis revealed:

- The Specific Energy Consumption (SEC) for methanol production was calculated using three methods. The most accurate, scaled from a real process, yielded a value of 2119 kJ/mol.
- This SEC is approximately three times higher than the Lower Heating Value (LHV) of methanol (638.1 kJ/mol), underscoring the energy-intensive nature of the process.
- The energy demand is primarily driven by DAC, AWH, and electrolysis (87%). Despite this, the modular design and site-specific optimization offer pathways to economic viability.

The energy balance served as the basis for simulation and optimization in later stages.

C. Future Energy System Modelling (FESM)

The FESM tool was used to evaluate location-specific feasibility and system sizing:

- Duqm emerged as the most favourable site due to its consistent solar irradiance, low seasonal variation, and competitive costs.

- A solar-only configuration in Duqm achieved a LCOE of 103.01 $/MWh.
- Duqm had the highest installed storage, yet Geraldton and Lüderitz showed a higher LCOE.

The FESM results provided directional insights for selecting Duqm as the base case location for autonomous modelling.

D. Modelling and Simulation

A custom simulation framework was developed in SciLab to evaluate autonomous operation under realistic conditions. Key findings include:

- The Base Case model achieved the monthly methanol production target of 30 tonnes, with a LCOE of 153.34 $/MWh. However, it experienced 156 hours of downtime, highlighting the need for predictive control.
- Configuration optimization delivered the optimal configuration set-up (lowest LCOE while obtaining the monthly methanol target) and revealed that smaller electrolyser sizes (1 MW vs. 1.5 MW) improved annual methanol output due to lower minimum operating thresholds.
- The Multi-Reactor model offered greater flexibility under constrained energy conditions, increasing the number of feasible configurations by 32% compared to the single-reactor setup.
- MPC strategies significantly improved operational stability:

  o The Basic weather MPC reduced downtime to 14 hours and achieved an LCOE of 153.34 $/MWh.

  o The Continuous weather MPC eliminated downtime entirely and improved constant system behaviour, but slightly reduced methanol output, resulting in an LCOE of 160.48 $/MWh.

  o The Uncertainty weather MPC, simulating forecast deviations, maintained uninterrupted operation with zero shutdown hours and met all monthly targets. The LCOE was 174.30 $/MWh, aligning with projected e-fuel costs for 2030 [10].

The projected costs for e-methanol 2030 are given in Figure 1, with corresponding production locations and shipping routes illustrated in Figure 2. These costs estimates are expressed in €/kWh and include transportation cost, while excluding taxes or profit margins. The production pathway was based on a DAC for CO_2 sourcing. In contrast, the simulated models developed in this study did not incorporate transportation costs. To address this, the costs of shipping e-methanol from Oman to the Netherlands were calculated as 9.99 $/MWh [10]. When converted to €/kWh, this results in a total $\text{LCOE}_{\text{production}}$ of 0.157 €/kWh under the uncertainty weather MPC scenario. This value aligns well with external projections for e-methanol costs in 2030, thereby confirming that the estimates derived in this study fall within the expected range of alternative production pathways (Figure 1).

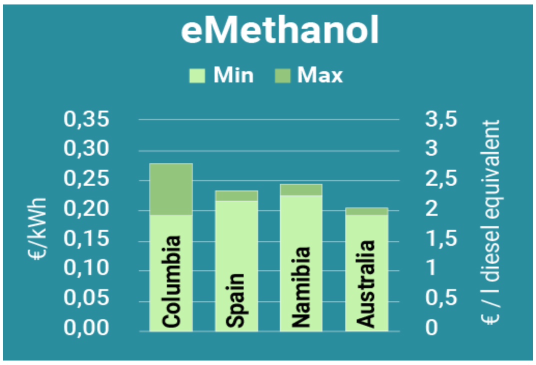

Fig. 1. Projected e-methanol production costs in 2030 [€/kWh] [10].

Fig. 2. E-methanol potential production locations and shipping routes to Europe [10].

These results demonstrate that predictive control is essential for autonomous operation, especially under variable solar conditions. The ability to maintain stable and consistent system behaviour, rather than frequent ramping or shutdowns is a key requirement for decentralized autonomous plants. Smooth operation reduces component stress, improves energy efficiency, and enhances system resilience. The uncertainty-aware MPC model showed that with well-tuned control logic and sufficient storage, the plant can operate continuously and reliably, even under (10%) forecast deviations. This confirms that predictive autonomy is not only feasible but necessary for achieving uninterrupted, scalable green methanol production in remote environments.

IV. CONCLUSION

This research set out to investigate the techno-economic feasibility of a decentralized autonomous green methanol plant powered by renewable energy sources. The study aimed to develop a concept that could operate independently in remote locations, using only renewable material inputs and -energy, while maintaining a stable and continuous methanol operation. The findings confirmed that such a system is technically viable and, under favourable conditions, and could achieve cost levels that are competitive with other projected e-fuels by 2030 [10].

A Specific Energy Consumption (SEC) of 2119 kJ/mol underscores the energy-intensive nature of the process. Among the evaluated locations, Geraldton (Australia), Lüderitz (Namibia), and Duqm (Oman), Duqm emerged as the most favourable site due to its consistent solar irradiance and competitive cost structure. For this location, the concept achieved a LCOE of 153.34 $/MWh in the Base Case and 174.30 $/MWh under the uncertainty-aware MPC scenario. The integration of MPC, particularly under weather uncertainty, proved essential for maintaining uninterrupted operation and minimizing downtime. Finally, the plant's modular design and simplified configuration enhance its autonomous capabilities while reducing operational risk.

The findings demonstrate that decentralized autonomous methanol production offers a scalable solution for sustainable fuel generation in remote and decarbonizing regions. By eliminating the need for grid connectivity, decentralized systems avoid transportation losses and infrastructure constraints, enabling deployment in locations where conventional energy systems are impractical. Autonomy further enhances operational resilience by minimizing labour requirements and allowing continuous, self-regulated operation with minimal human oversight. The concept contributes to the broader field of autonomous renewable chemical production and supports the transition toward distributed, resilient energy systems.

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