



ORIGINAL RESEARCH ARTICLE

HYBRID RENEWABLE-HYDROGEN AND NATURAL GAS METHANOL SYNTHESIS: A TECHNO-ECONOMIC ANALYSIS

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ABSTRACT

Conventional methanol production is highly carbon-intensive due to its reliance on fossil-derived hydrogen from reforming processes. The purpose of this study is to assess the viability of incorporating renewable hydrogen from solar-powered electrolyzers to reduce the environmental impact of natural gas-based methanol production and replace the requirement for reformer hydrogen. Aspen HYSYS 14.0 was used to model and compare two hybrid configurations: Steam Methane Reformer–Autothermal Reformer (SMR–ATR) with electrolyzer and Autothermal Reformer–Heat Transfer Exchange Reformer (ATR–HTER) with electrolyzer, with their conventional counterparts in a steady-state techno-economic and environmental assessment. All process configurations' technical viability was confirmed by mass and energy balance analyses. The findings showed that the configurations differ significantly in terms of production costs, methanol purity, and utility demand. Although it produced methanol with a purity of only 50.43%, requiring downstream upgrading, the SMR–ATR with electrolyzer design achieved the lowest levelized cost of methanol (LCOM) at USD 95.29 per tonne and the lowest utility requirement (468,113 kWh). The ATR–HTER with electrolyzer design, on the other hand, needed a significantly higher electricity consumption of about 11.76 million kWh, raising the LCOM to USD 119.12 per tonne despite achieving high methanol purity (98.56%) and efficient renewable hydrogen integration. These results suggest that excessive energy usage might negatively impact economic performance, even if electrolyzer integration can improve carbon efficiency and lessen reliance on fossil-based hydrogen when powered by low-carbon electricity. Overall, electrolyzer-assisted methanol production is most economical in regions with plentiful natural gas and access to low-cost renewable electricity, such as Nigeria, which helps to advance United Nations Sustainable Development Goals 7, 9, and 13.

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1.0 Introduction

The demand for methanol, a precursor to formaldehyde, dimethyl ether, and synthetic fuels, currently exceeds 100 million tonnes per year worldwide. This makes it one of the most significant building blocks of the chemical industry (IEA, 2023). The efficient (in terms of hydrogen yield and process maturity) but extremely carbon-intensive processes of steam or autothermal reformation of natural gas are the mainstays of conventional

production because their long-term sustainability is threatened by the significant CO₂ emissions caused by the production of hydrogen from fossil fuels. As the need to decarbonize heavy industry grows, incorporating renewable hydrogen through electrolyzers into traditional methanol plants has become a viable option to lessen carbon intensity and reliance on fossil fuels (Cameli *et al.*, 2024; Liu *et al.*, 2024). On the other hand, electrolyzer-assisted reforming requires a rigorous techno-economic evaluation under realistic conditions, as it profoundly alters reaction equilibria, mass and energy balances, and downstream separation needs (Abdulsalam *et al.*, 2020; Cameli *et al.*, 2024; Liu *et al.*, 2024).

Nigeria provides an especially interesting backdrop for researching these hybrid systems. Nigeria has proven natural gas reserves of over 200 trillion cubic metre (NNPC, 2024), and it frequently burns enormous amounts of associated gas, which is a waste of money and an environmental problem (Okoro *et al.*, 2021). However, with an average of 5–6 kWh/m²/day in most regions, Nigeria has some of Africa's highest levels of solar irradiation (IRENA, 2023). This makes solar-powered electrolyzers physically feasible. By exploiting this twin availability of solar energy and natural gas, Nigeria may jump straight to the manufacturing of lower-carbon methanol, converting flared gas into feedstock and using renewables to provide oxygen and hydrogen (IRENA, 2023). Few studies have methodically examined traditional and electrolyzer-assisted methanol production processes within a consistent modeling framework using assumptions indicative of emerging-economy settings, despite the growing interest in low-carbon methanol. Without specifically assessing hybrid configurations that incorporate electrolytic hydrogen into traditional reforming pathways, most current studies either concentrate on hypothetical "green" methanol plants based only on captured CO₂ and electrolytic hydrogen or evaluate natural-gas reforming-based methanol production in isolation. These studies usually show that incorporating renewable hydrogen can enhance sustainability indicators and lower carbon intensity, but they don't assess the overall effects on product purity, process efficiency, and economics across various reforming configurations. (Pérez-Fortes *et al.*, 2016; Cameli *et al.*, 2024). Notably, no previous research has directly examined the steam methane reformer-autothermal reformer (SMR-ATR) and autothermal reformer-heat transfer exchange reformer (ATR-HTER) approaches in their electrolyzer-assisted versions. Evaluating these specific pairings is critical because SMR-ATR and ATR-HTER have different hydrogen production mechanisms, energy integration, and downstream methanol synthesis properties, which can have a significant impact on utility demand, methanol purity, and overall techno-economic and environmental performance.

Three significant contributions are made by this research to the global conversation on decarbonizing the manufacture of methanol. First, assuming consistent assumptions, it provides comprehensive mass and energy balances for electrolyzer-assisted pathways, therefore bridging the empirical gap. Secondly, it provides a comprehensive decision framework by connecting these technical measurements to environmental indicators and economic performance (levelized cost of methanol, NPV, and IRR). Third, by focusing on Nigeria's distinct resource profile, the analysis shows how gas- and solar-rich nations can align industrial development with the Sustainable Development Goals of the UN, particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action), while also establishing a model for economies of a similar nature around the world.

2. Materials and Methods

2.1 Process overview

"Techno-economic evaluation of two different process configurations for methanol production from natural gas, with the integration of a solar-powered electrolyzer" is the main objective of this study. The simulation was done with Aspen HYSYS V14.0, a software developed by Aspen Tech®. It was chosen due to its strong chemical engineering databases, adaptability in process design, flexibility, ease in handling, user-friendly, and high-accuracy modeling of integrated thermal, chemical, and electrochemical systems. The two routes begin with natural gas pre-treatment and reforming to produce synthesis gas, which is then converted to methanol over copper-based catalysts at high pressure and moderate temperature.

2.1.1 Process description

Five thousand kg/hr of natural gas with a composition from the work of McCaul 2019 (Table 1) was compressed and added to the system at 25 °C and 1 bar in the SMR-ATR and ATR-HTER setup. After heating up, it was delivered to the desulphurizer. To safeguard catalysts downstream, this unit eliminates sulphur compounds. After combining steam and heating it to 500 °C, the sweetened natural gas was transported into a steam reformer, which transformed the superheated, desulfurized, methane-rich natural gas-steam mixture into syngas based on equation 1.

Table 1: Natural Gas Feed Composition

S/N	Components	Molecular Formula	Mass fraction
1	Methane	CH ₄	0.950521
2	Carbon dioxide	CO ₂	0.00501
3	Oxygen	O ₂	0.000193
4	Nitrogen	N ₂	0.017736
5	Ethane	C ₂ H ₆	0.024226
6	Ethene	C ₂ H ₄	0.00231



A low operating temperature at the reformer tube exit limits the reaction. After that, the syngas effluent was directed to an autothermal reformer (ATR). In the ATR-HTER configuration, a component splitter was used to transport 80% of the input stream into the ATR (at 1000 °C and 1.8 bar) after the sweetened natural gas and steam were mixed. The ATR provided heat for reformer tubes, which reformed 20% of the natural gas intake at a higher S/C (2.0). According to Arnaiz del Pozo *et al.* (2022), such a setup makes it easier to achieve an appropriate conversion rate.

A solar-powered electrolyzer was used to split demineralized water into hydrogen and oxygen. To supplement the syngas stream and lessen the requirement for hydrogen obtained from fossil fuels, the split hydrogen (H₂) was directed into the reforming portion. The feed gas was combined with oxygen (O₂) from the electrolyzer to provide heat for further reforming in the catalyst section of the ATR (Nwosu *et al.*, 2021), based on equation 2.



A heat transfer exchanger reformer (HTER) that operates in parallel with the ATR receives the exit stream after that. Using heat from the ATR outlet and the HTER's reformed product, 20% of the natural gas input was reformed in reformer tubes at a higher S/C (2.0). Equation (3) illustrates how methane and superheated steam combine in the HTER to create syngas.



The syngas product was further cooled to 200 °C in a series of heat recovery. After a final heat rejection, the syngas was routed to the synthesis loop, where methanol was produced based on equation 4.



The saturated methanol stream was separated from the fuel gas and other light gases by directing the product into a separator. The methanol stream was further refined in a second separator, where water was removed, to create a pure methanol stream. The superheated fuel gas was then recycled to preheat the entrance natural gas streams to the HTER and ATR after being heated by the knock-out water (steam). The fluid package transitions of streams to unit blocks operating on a particular basis were satisfied using component splitters.

The Electrolyzer simulation involves the use of Aspen properties in formulating the component list, and reactions were generated using the electrolyte wizard, which includes the chemistry dissociation and chemistry equilibrium reactions as shown in equation (5):



The reactions involved in the generation of the anode (Oxygen) and cathode (Hydrogen) are shown in equations (6–):



Figures 1 and 2 represent a detailed process flow diagram of the process configuration.

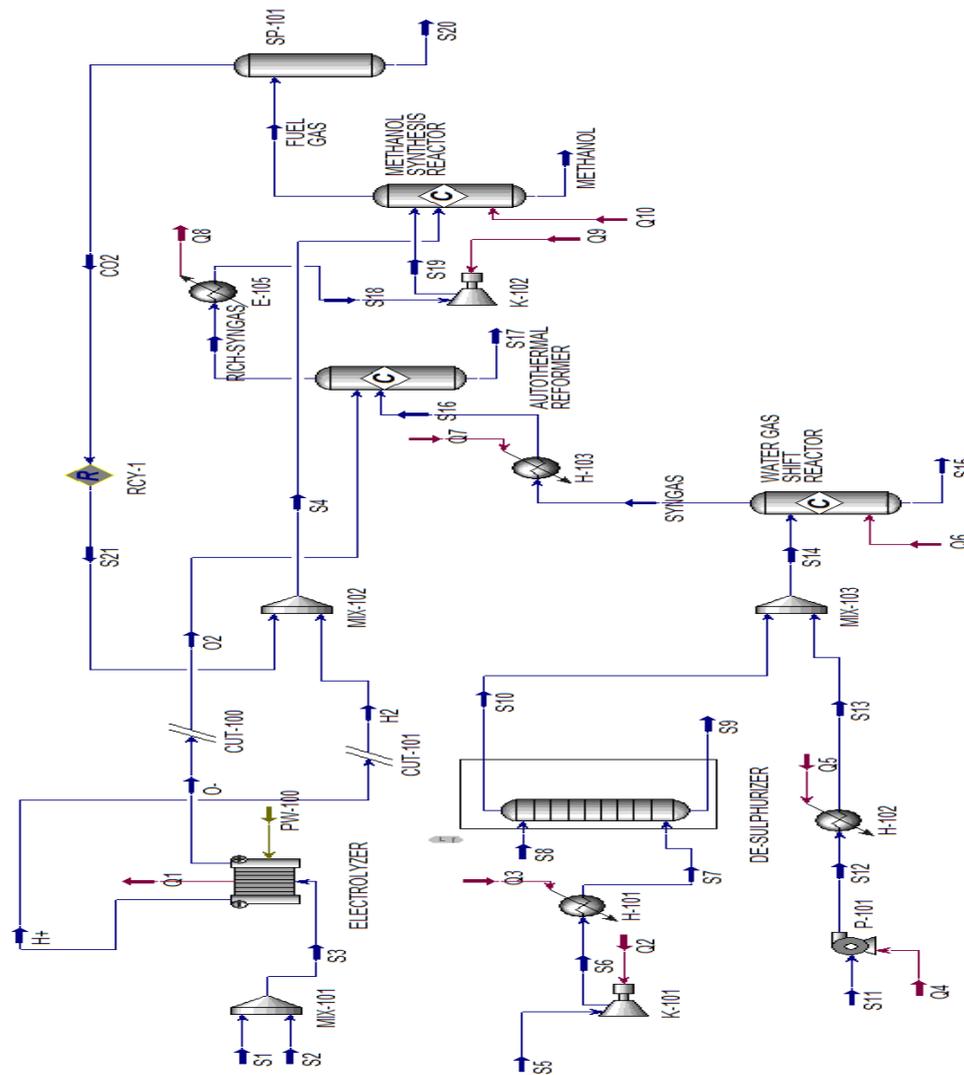


Figure 1: Process flow diagram for Steam Methane Reformer – Autothermal Reformer with Electrolyzer configuration

2.2 Economic Analysis

Economic analysis of the successfully converged process was carried out, which consists of Total Capital Cost, Total Operating Cost, Total Installation Cost, Equipment costs, and utility costs; the total utilities combine both the heating and cooling utilities. The estimation of the cost is based on the cost index of 2019 provided by Aspen Econs and assuming a 24/7 electricity supply. The economic assumptions made for this work are highlighted in Table 2

Table 2: Economic Assumption

Items	Price/unit
natural gas	\$2.63 MMBTU
total raw material cost	\$5,459,580/year
Discount rate	20%
Period	10 years
Economic indicator (base price methanol price)	\$300/tonne
Sensitivity analysis	±10 – 25

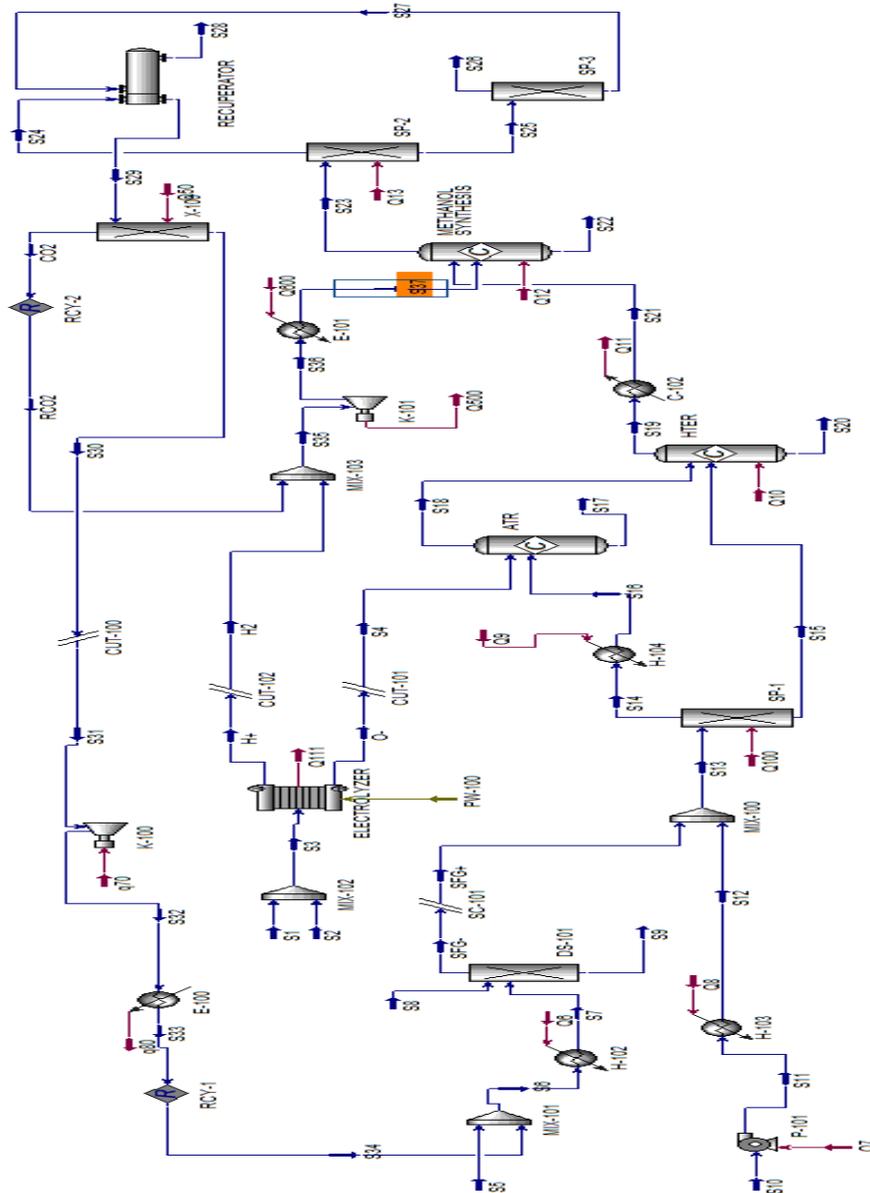


Figure 2: Process flow diagram for Autothermal Reformer–Heat Transfer Exchanger Reformer with Electrolyzer configuration

3. Results and Discussion

This section includes an economic and technological examination of methanol produced via two different configurations from natural gas and electrolysis using Aspen HYSYS.

3.1 Technological Assessment

The overall energy balance, mass balance, and process efficiencies of two process configurations intensive yet nevertheless generate a surplus, as evidenced by the net energy gain of 2.91×10^1 kJ/hr. The ATR-HTER with electrolyzer configuration, on the other hand, achieved an energy output of 1.53×10^6 kJ/hr with a far lower energy input of 1.45×10^6 kJ/hr. This resulted in a little net gain of 8.01×10^2 kJ/hr. The ATR-HTER with electrolyzer configuration arrangement indicated superior energy efficiency, generating a comparable output with significantly less energy demand, whereas the SMR-ATR configuration displayed a higher numerical net gain because of its huge scale. This implies that the ATR-HTER with the electrolyzer system has better heat integration and fewer losses (Nakashima et al., 2025). Perfect mass balance was maintained by both systems, with equal mass intake and output (≈ 1.6 million kg/hr for SMR-ATR with electrolyzer configuration and ≈ 1.36 million kg/hr for ATR-HTER with electrolyzer configuration). These zero accumulations indicated that there was no material buildup inside the system boundaries, and both designs functioned under steady-state conditions. The mass fraction and mass flow rate, which indicate how well each system uses or transforms feedstock, are where the differences occur. With a mass fraction of 50.43%, the SMR-ATR with electrolyzer configuration contributed almost half of the entering material to the usable output

stream. The ATR-HTER with electrolyzer configuration exhibited a significantly higher mass fraction of 98.56%, indicating better input feed utilization and conversion efficiency. Additionally, the mass flow rate in ATR-HTER (9625.72 kg/hr) was higher than in SMR-ATR (8919.69 kg/hr), indicating that the ATR-HTER configuration can process materials more efficiently and with higher throughput. Overall, the data clearly showed that the ATR-HTER with electrolyzer configuration is the most effective and optimized process, providing improved throughput, higher mass conversion efficiency, and better energy utilization. This makes it a more appealing option for thermochemical processes requiring the effective integration of reforming and electrolysis technologies, such as those involving the production of hydrogen or syngas.

Table 3: Energy and Mass balance results of two different configurations

Description	Unit	SMR-ATR with electrolyzer	ATR-HTER with electrolyzer
Total Energy in	KJ/hr	-6026107038	1451966627
Total Energy Out	KJ/hr	-5735549495	1532101573
Net loss or Gain	KJ/hr	290557542.7	80134946.21
Total Mass in	Kg/hr	1603716	1357301
Total Mass out	Kg/hr	1603716	1357301
Net Accumulation	KJ/hr	0	0
mass fraction	%	50.43	98.56
Mass Flow	kg/h	8919.69	9625.72

3.2 Economic Result

The economic analysis of these processes was conducted in this study using APEA®. A comparative techno-economic analysis was performed for the SMR-ATR with electrolyzer and ATR-HTER with electrolyzer configurations, using detailed capital cost breakdowns, operating expenditures, discounted cash-flow (DCF) trends, and levelized cost of hydrogen (LCOM). The results clearly highlighted the economic strengths and constraints of each configuration.

The total cost breakdown for the two setups is shown in Figures 1 and 3. Due mainly to cheaper equipment and installation costs, the SMR-ATR with electrolyzer system has a lower total capital cost. The SMR-ATR with electrolyzer configuration needs relatively fewer high-temperature and high-pressure components, as evidenced by the fact that its total installed cost was still much lower than that of the ATR-HTER with electrolyzer design. A more equitable cost distribution is also the outcome of the modest demands for utilities and raw materials.

The ATR-HTER with electrolyzer configuration, on the other hand, exhibits much higher capital and raw material costs due to the higher heat requirements and more intricate reactor architecture in the high-temperature electrochemical reforming segment. The main financial burden resulted from the increased feed intake and operational energy intensity, which together raise the overall installed cost, even though equipment costs rise somewhat. The discounted Cash Flow progression during the project's ten years is shown in Figures 2 and 4. Following the first year of negative investment, the SMR-ATR with electrolyzer configuration shows a substantial positive cash flow and a quick early recovery. After that, cash flow gradually decreases as annual sales stabilize and output matures. The DCF pattern shows that the SMR-ATR with electrolyzer configuration maintains stable economic performance and quickly reaches a favourable net present value.

The trajectory was more complicated in the ATR-HTER with electrolyzer arrangement. Its cash-flow values are often less steady and not as consistently high as those of the SMR-ATR with electrolyzer configuration, despite a notable cash-flow surge around Year 5, which is probably related to operational optimization or planned scale-up. Net annual profitability was lowered by the higher initial capital load and increased operating input. Consequently, total discounted revenue accumulation is still less favourable despite sporadic peaks.

Figure 5 compares LCOM values to offer a convincing economic conclusion. The ATR-HTER with electrolyzer configuration displays a much higher LCOM of \$119.12/tonne, whereas the SMR-ATR with electrolyzer pathway produced a much lower LCOM of \$99.29/tonne. This was as a result of the SMR-ATR system's better operating economics as well as its reduced initial expenditure. The cost advantage showed that adding an electrolyzer to the SMR-ATR sequence improved hydrogen yield without sacrificing profitability.

Overall, the SMR-ATR with electrolyzer configuration was more cost-effective across all measures, including capital cost, discounted cash flow, and LCOM. Its reduced cost per tonne of hydrogen, steady long-term cash inflow, and cheaper installation costs highlight its appropriateness for industrial-scale deployment. In the

meantime, the ATR–HTER with electrolyzer configuration offers operational benefits (such as increased thermal efficiency), but its high-cost structure presents significant financial difficulties. The ATR-HTER with electrolyzer configuration is still less commercially appealing unless new catalysts or developments in heat recovery drastically lower its material and utility requirements. Figure 6 presents the graph of discounted cash flow for ATR-HTER with Electrolyzer configuration.

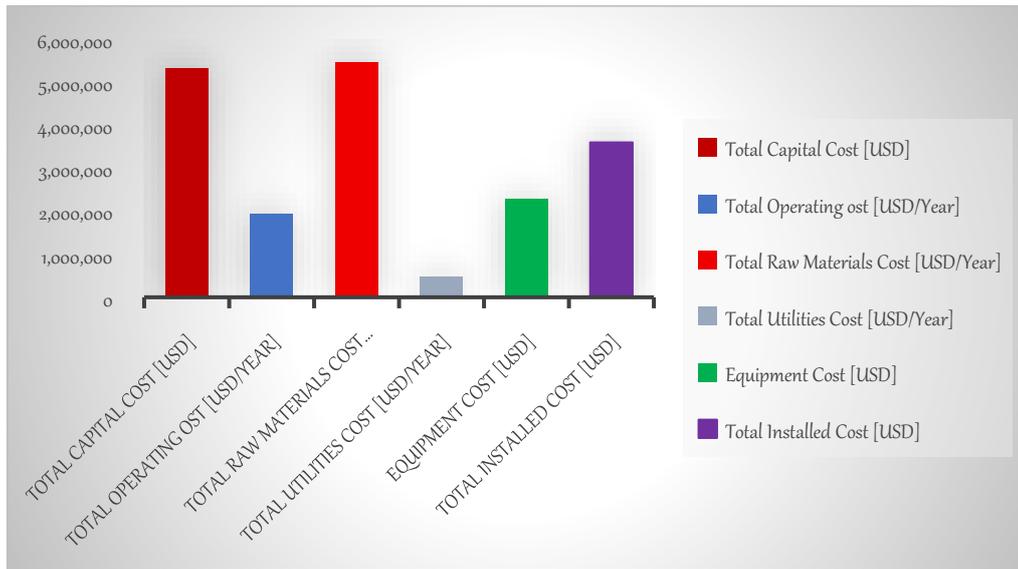


Figure 3: Chart of the Cost Analysis for SMR-ATR with electrolyzer configuration

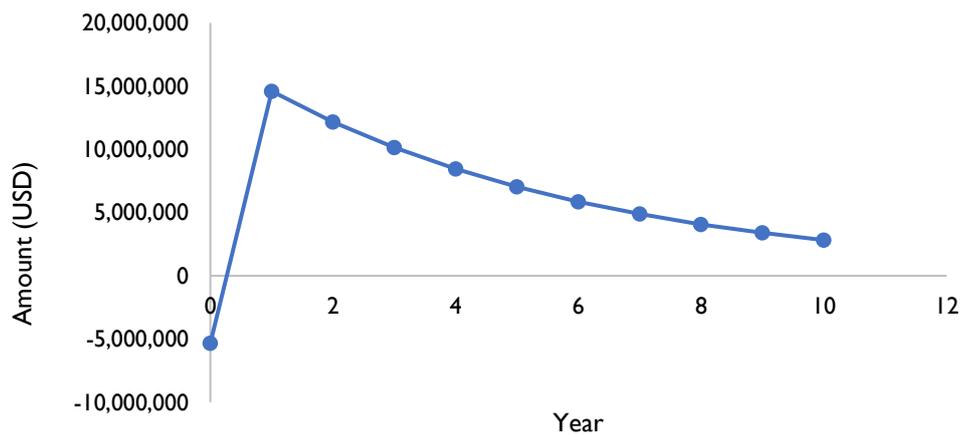


Figure 4: Graph of Discounted Cash Flow for SMR-ATR with electrolyzer configuration

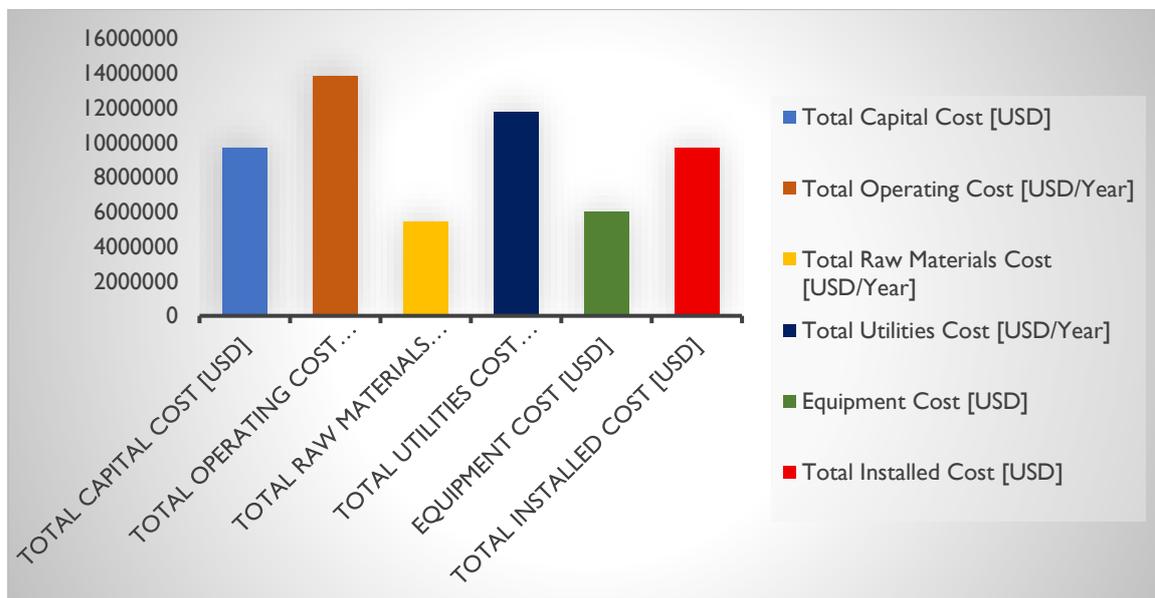


Figure 5: Chart of the Cost Analysis for ATR-HTER with electrolyzer configuration

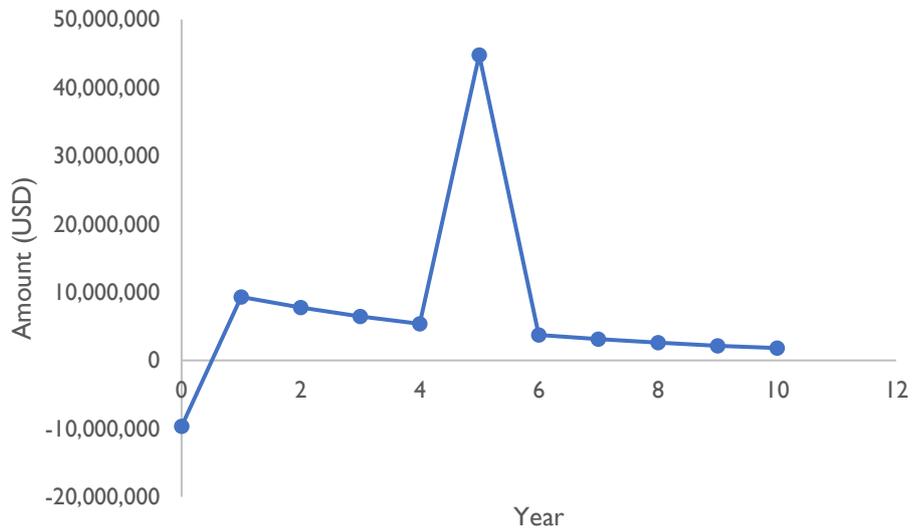


Figure 6: Graph of Discounted Cash Flow for ATR-HTER with Electrolyzer configuration

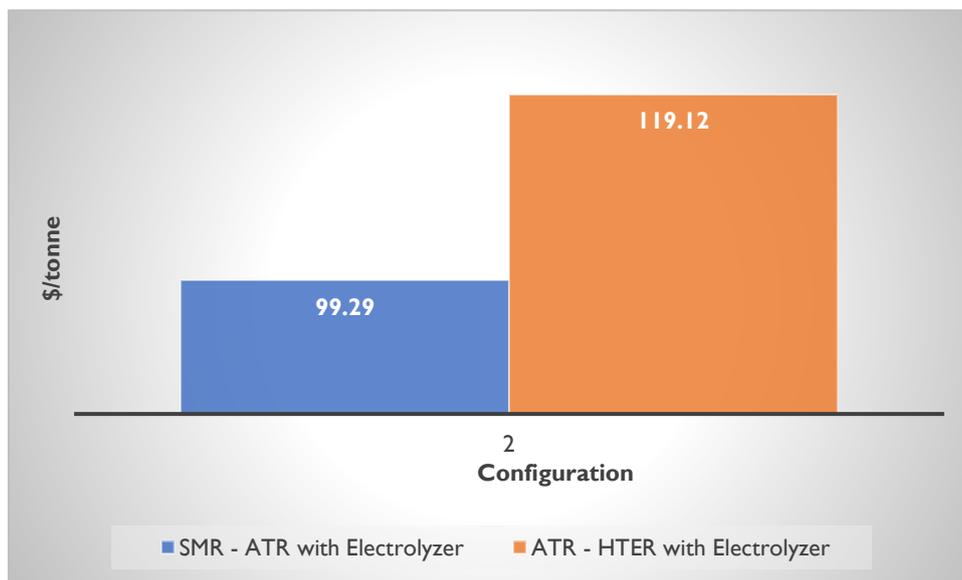


Figure 7: Chart of the levelized cost of the configurations

4. Conclusion

This study showed that electrolyzer integration into conventional methanol production allowed for a trade-off between economic performance and process efficiency. The SMR–ATR configuration with electrolyzer offered a lower levelized cost of methanol and reduced utility demand, but it produced methanol below industrial-grade purity, which limits its immediate applicability without further downstream upgrading. In contrast, the ATR–HTER configuration produced high-purity methanol and superior energy efficiency, but at higher capital and utility costs. These results showed that choosing the best approach relies on regional priorities: SMR-ATR may be preferred in cost-sensitive situations, whereas ATR-HTER's efficiency and product quality benefits may be utilized in areas with access to inexpensive renewable electricity or prospects for heat recovery. ATR-HTER's competitiveness might be further increased by focused capital reductions and process optimization, establishing it as a viable route for the manufacture of low-carbon, sustainable methanol.

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