Proceedings of ICEGEE 2025 Symposium: Sensor Technology and Multimodal Data Analysis
DOI: 10.54254/2753-8818/2025.AU24061

Techno-Economic Assessment of a Closed-Loop Methanol Fuel System for Maritime Decarbonization

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Abstract: Maritime transport with the contribution of 2.89% to global CO_2 emissions is with urgent imperatives to be decarbonized. Based on such closed loop methanol fuel system, including methanol combustion, onboard CO_2 capture and methane resynthesis to produce near zero emissions, this study assesses the financial viability. We evaluate a 10 year project horizon through NPV using a MATLAB-based Net Present Value (NPV) model based on the current cost and policy conditions with a negative NPV of €13.44 million for a Baltic Sea ferry. Retrofit costs, however, are high, as are hydrogen expenses and limited policy support, which demonstrate the inability of the technology to be viable without stimulus from regulation and technological advancement. In addition, sensitivity analyses show that increasing the carbon tax or decreasing the cost of hydrogen will lead to positive NPV. The study shows how policy incentives can play such a crucial role in fostering the adoption of low carbon maritime technologies. The closed loop methanol system is financially unsuitable without significant hydrogen cost reductions or the introduction of much higher carbon taxes. Also, the technological advancement in onboard CO_2 capture and efficiency in methane synthesis could also tilt the economics in the favor. Overall, the maritime sector is required to decarbonize, but this drive can best be carried out through a coordinated effort amongst regulatory bodies, industry stakeholders, and technology developers.

Keywords: Closed-loop methanol system, Carbon capture and utilization (CCU), Net Present Value (NPV), Techno-economic assessment, Hydrogen cost reduction

1. Introduction

The maritime sector, a cornerstone of global trade, accounts for approximately 2.89% of anthropogenic CO_2 emissions, equivalent to 1,076 million tonnes annually. New solutions to fight emissions are essential given that the International Maritime Organization (IMO) wants up to 50 percent reduction in emissions by 2050. The amounts of emissions reduction potential with methanol, a low sulfur alternative fuel, are high and especially so when partnering that fuel with onboard carbon capture and utilization (CCU) in a closed loop system. Methanol is combusted under this system, its resulting CO_2 is captured and resynthetised into methanol using renewable hydrogen with a goal of nearly zero emissions cycle.

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DOI: 10.54254/2753-8818/2025.AU24061

Although it is an environmentally promising technology, the economic viability remains a termination. The techno-economic assessment of a piece of this route was conducted in this study using a Net Present Value (NPV) model developed in MATLAB. Costs, revenues and policy impacts are analyzed for adoption barriers and enablers, respectively. To be a contribution to the maritime decarbonization debate, we quantify economic challenges and give actionable solutions.

2. Literature review

As the maritime sector is large CO_2 emitter and the IMO has ambitious 2050 targets, the subject of its decarbonization has been receiving significant research attention. Although vaporization of sulfur performed on therypted mother lithium is not intensive as sulfur burning byproduct removal, studies highlight other fuels including liquefied natural gas (LNG), hydrogen, and methanol as top choices for emission reductions with methanol receiving interest due to its lower sulfur content and compatibility with existing infrastructure. According to Andersson [1], methanol has the potential to be a marine fuel since it is able to control sulfur oxides (SOx) reductions to 99 percent and nitrogen oxides (NOx) reductions as high as 60 percent compared to heavy fuel oil. The reporting expires when the products are placed into use in everyday life, but they warn that emissions over product lifecycles depend on how these products are produced, with green methanol (produced from renewable hydrogen and CO2) having almost zero emissions but also very high costs.

Carbon capture and utilization onboard (CCU) has become a complementary strategy to boost alternative fuels' environmental benefits. Thaler et al. (2022) [2] investigate amine based CO_2 capture on LNG fueled ships showing 85–90% capture efficiencies with penalties of 10–15% in energy which puts a heavy burden on the fuel consumption. Onboard CO_2 capture that provides guidance on modelled costs of €100–200/ton CO_2 for bulk carriers, based on energy intensive scrubbing and storage. Spatial constraints and high retrofit costs, in particular for smaller vessels such as ferries, are the only barriers cited in these studies to CCU's technical feasibility.

Less work has been done with closed loop systems incorporating CCU with fuel resynthesis. In accordance with Feenstra[3], a closed-loop methanol system would achieve 70–80% reduction in net emissions, however, hydrogen costs (€3–5/kg) and proximity of synthesis facility are cited as economic hurdles. However, foresees that costs of green hydrogen will reach €1/kg by 2035 [4], making the technology viable, but current policy frameworks, including the EU Emissions Trading System (ETS)[5], failing to fully utilize carbon capture and storage (CCS) capabilities, while also not properly accounting for CO_2 captured during green hydrogen production. Plausible gaps (high costs, policy misalignment, low integration of CCU with fuel resynthesis) justify this study's focus on a techno-economic assessment of a closed loop methanol system with a specific detail on a NPV analysis and the policy recommendations.

3. Methodology

3.1. System overview

The closed-loop methanol fuel system comprises:

1) Methanol Dual-Fuel Engines: Power the vessel, burning methanol to produce energy and CO_2.
2) Amine-Based CO_2 Scrubbers: Capture 90% of exhaust CO_2 using monoethanolamine (MEA) or MDEA/PZ solvents.
3) Pressurized Storage Tanks: Store liquid CO_2 at 15 bar, -20°C, for offloading at port.
4) Port-Based Methanol Synthesis: Combines captured CO_2 with renewable hydrogen (via electrolysis) to regenerate methanol.

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The system is evaluated for a roll-on/roll-off passenger (RoPax) ferry operating between Stockholm, Sweden, and Helsinki, Finland (220 nautical miles), a route ideal for frequent CO_2 offloading.

3.2. NPV framework

NPV assesses financial viability by calculating the present value of future cash flows, discounted to reflect the time value of money:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t}$$

1) Ct: Net cash flow at year (t) (inflows minus outflows).
2) r : Discount rate (8%, reflecting maritime investment risk).
3) n : Project lifetime (10 years, standard for retrofit projects).

A positive NPV indicates a profitable investment, while a negative NPV suggests economic non-viability without external support.

3.3. Case study context

With existing methanol bunkering infrastructure at the Port of Stockholm, Stockholm–Helsinki route can sustain daily operations (365 trips/year). The ferry, 35,000 gross-tonne vessel, uses 30 tonnes of methanol a day and stores 41, captures 41 and releases 37. During refueling offloads CO_2 and transports the gas 10 km to a modular synthesis facility.

3.4. Economic assumptions

The NPV model incorporates parameters derived from industry data. In Table 1 summarizes the key assumptions used in the NPV model.

Table 1: NPV model assumptions

Parameter	Value
Project duration	10 years
Discount rate ((r))	8%
Initial retrofit cost (CapEx)	€15 million
Annual CO_2 capture & transport	€4 million
Annual maintenance	€1.5 million
Fuel penalty (10% of €20M fuel)	€2 million
Methanol price growth	10% per annum
Hydrogen cost (declining)	€ 4/kg (Year 1) → € 1/kg (Year 10)
CO_2 captured annually	37,000 tonnes
Carbon tax savings	€100/ton = €3.7 million/year
Internal methanol savings (Year 1)	€2.5 million

Assumptions:

1) CapEx: Includes amine scrubbers, storage tanks, and engine conversion (€250–550/kW).
2) OpEx: Capture costs €108/ton (mid-range estimate), transport €10/ton.
3) Revenues: Carbon tax savings assume partial EU ETS exemption; methanol savings grow with market prices.
4) Hydrogen: Declines linearly, reflecting projected electrolysis cost reductions.

DOI: 10.54254/2753-8818/2025.AU24061

3.5. Program code

```
% compute_closed_loop_npv_with_plot.m
% Calculate and plot NPV for a closed-loop methanol fuel system
(10-year horizon)

%% 1. Project Parameters
years       = 0:10;           % 0 = today, 1–10 = years ahead
r           = 0.08;           % discount rate (8%)
nPeriods    = length(years);

% Initial Capital Expenditure (Year 0)
capex       = 15e6;           % €15 million retrofit cost

% Annual Base Costs (Year 1–10)
annualCaptureCost    = 4.0e6;    % CO₂ capture & transport (€ per
year)
annualMaintenance    = 1.5e6;    % Maintenance (€ per year)
annualFuelPenaltyPct = 0.10;     % 10% extra fuel consumption
penalty
annualFuelBaseCost   = 20e6;     % Base fuel bill (€ per year)

% Annual Revenues/Savings (Year 1–10)
annualMethanolCostSaved = 2.5e6;    % Internal methanol production
savings (€ in Year 1)
annualCarbonTaxSaved    = 100 * 37e3;  % €100/ton × 37 000 t CO₂ =
€3.7 M

% Growth / Decline Assumptions
methanolPriceGrowth = 0.10;                 % 10% p.a. increase
hydrogenCostFall    = linspace(4, 1, nPeriods);
% €4/kg in Year 1 → €1/kg in Year 10

%% 2. Preallocate cash-flow vectors
netCF = zeros(1, nPeriods);
pvCF  = zeros(1, nPeriods);

%% 3. Build Yearly Cash Flows
for t = 1:nPeriods
    if years(t) == 0
        % Year 0: only the capex
        netCF(t) = -capex;
    else
        % Year t > 0
        fuelPenaltyCost = annualFuelBaseCost *
annualFuelPenaltyPct;
        captureCost     = annualCaptureCost;
        maintCost       = annualMaintenance;
```

DOI: 10.54254/2753-8818/2025.AU24061

```
        synthCost       = hydrogenCostFall(t) * 37e3;
        % assume 37 000 kg H₂ each year

        totalOutflow = fuelPenaltyCost + captureCost + maintCost +
synthCost;

        methSaved    = annualMethanolCostSaved * (1 +
methanolPriceGrowth)^(t-1);
        taxSaved     = annualCarbonTaxSaved;
        subsidy      = 0;  % add if modelling grants

        totalInflow  = methSaved + taxSaved + subsidy;

        netCF(t) = totalInflow - totalOutflow;
    end

    % Discount to present value
    pvCF(t) = netCF(t) / (1 + r)^years(t);
end

%% 4. Compute NPV
NPV = sum(pvCF);

%% 5. Display Numerical Results
fprintf('Year\tNet CF (€)\tPV of CF (€)\n');
for t = 1:nPeriods
    fprintf('%2d\t%12.0f\t%12.0f\n', years(t), netCF(t), pvCF(t));
end
fprintf('-------------------------------------\n');
fprintf('Total NPV over %d years: €%.0f\n', years(end), NPV);

%% 6. Plot Results
figure;
plot(years, netCF/1e6, '-o', 'LineWidth', 1.5)
hold on
plot(years, pvCF/1e6, '-s', 'LineWidth', 1.5)
hold off
grid on
xlabel('Year')
ylabel('Cash Flow (€ million)')
title('Closed-Loop Methanol System: Net vs PV Cash Flows')
legend('Net Cash Flow', 'PV of Cash Flow', 'Location',
'NorthWest')
```

4. Results

A MATLAB model was developed to compute year-by-year cash flows and their present values, integrating dynamic inputs such as methanol price growth and hydrogen cost declines.

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In Table 2 presents the year-by-year results of the NPV model, including both net and present value cash flows.

The model outputs:

Table 2: The model results

Year	Net Cash Flow (€)	Present Value of Cash Flow (€)
0	-15,000,000	-15,000,000
1	-1,186,900	-1,098,981
2	-900,800	-772,291
3	-587,200	-466,138
4	-243,350	-178,870
5	133,775	91,045
6	547,503	345,019
7	1,001,493	584,361
8	1,499,772	810,280
9	2,046,769	1,023,894
10	2,647,356	1,226,238
Total NPV	—	€-13,435,442

Graphical Analysis

The cash flow trajectory (Figure 1) transitions to positive net flows after Year 4, driven by growing methanol savings and declining hydrogen costs. However, the high initial retrofit cost and early-year losses result in a negative NPV.

As shown in Figure 1, the net cash flow becomes positive after year 4 due to increasing methanol savings and decreasing hydrogen costs.

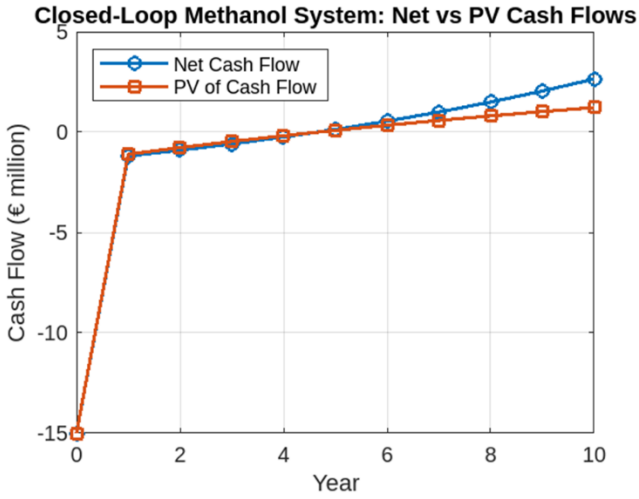


Figure 1: Net cash flow trajectory

5. Discussion

The negative NPV of €13.44 million underscores significant economic barriers to the closed-loop methanol fuel system's adoption. The main cause of this result is the massive €15 million Cappex requirement for retrofitting the vessel with amine based scrubbers, pressurized CO_2 storage tanks and methanol compatible engine sorts. These upfront costs generate a financial burden that later cash inflows (€3.7 million/year from carbon tax savings and €2.5 million/year from the internal methanol

DOI: 10.54254/2753-8818/2025.AU24061

production savings with a growth rate of 10% per year) are unable to cover before the 10-year horizon. Further exacerbating the negative NPV is the discount rate of 8%, representing the maritime sector's investment risk, that reduces present value even further and further reduces the NPV of future gains.

However, the critical cost driver is hydrogen costs going down from €4/kg to €1/kg over the project life time. Furthermore, methanol synthesis still generates a cost of €1.5 million during the early years of the process due to the requirement of energy intensive and costly green electricity to produce renewable hydrogen through electrolysis. Projections also assume a linear decline to €1/kg but the EVISC interest rate and necessary electrolyzer efficiency and renewable energy scalpability imply much greater effort to achieve €1/kg by 2035. Otherwise synthesis is a bottleneck.

Policy gaps further hinder viability. Under the EU Emissions Trading System (ETS)[5], for which maritime emissions will be effective from 2024, a €100/ton CO_2 tax is imposed relative to which partial exemptions for captured CO_2 yield only €3.7 million/year saving. Captured CO_2 could be fully recognized for tax purposes as being 'green' with no tax liabilities increasing savings to €7.4 million/year from €3.7 million/year. Likewise, subsidies on par with the U.S. 45Q credit (€50/ton) would not be sufficient; a €2 million/year gift would make a big difference in NPV. However, IMO incentives for CCU technologies do not exist hence there is a need for regulation change.

In MATLAB, sensitivity analyses are conducted that show pathways to positive NPV. Increasing the carbon tax to €200/ton pushes NPV to approximately -€2.5 million annual revenues is doubled to €400/ton, causing a FY2019 government revenue increase from €800 to €1,200 million[6]. The near zero NPV caused by the higher taxes won in the base case depends on whether or not the costs for hydrogen can be brought down to €0.5/kg by Year 5, which in turn brings the synthesis costs to €0.75 million getting it closer to zero. The combination of a €200/ton tax, a €0.5/kg hydrogen, and a €1 million/year generosity subsidy has a positive NPV of €10 million and shows how policy and technology can complement each other. These findings highlight that economic viability would hinge on the progress in the cost structures and the regulatory frameworks.

Barriers overcome need the collaboration of stakeholders. CO_2 offloading infrastructure for modular facilities can only be provided by partnered ports, while synthesis operators and their partnerships are necessities for shipowners to deal with high financial risks. R&D funding and tax incentives should help governments to accelerate the adoption as with the EU's FuelEU Maritime initiative[7]. These efforts are justified by the environmental benefits the system could provide, namely, the avoidance of 37,000 tonnes of CO_2 annually per vessel, but economic viability remains the critical hurdle.

6. Case study: Stockholm–Helsinki ferry route

The use of the closed loop system is applied to a RoPax ferry on the Stockholm–Helsinki route, a 220 nautical mile journey across the Baltic Sea[8], which lends itself to frequent CO_2 offloading since the ferry will have daily port calls. It (the ferry) has a gross tonnage of 35,000 and has two Wärtsilä methanol dual fuel engines (17 MW in comp.); it uses 30 tonnes of methanol daily and has a CO2 emission of 41 tonnes per day. At an efficiency of 90%, the amine based capture system captures 37 tonnes of CO2 a day and incurs a 10% fuel penalty which results in 3 tonnes of methanol to be consumed a day. CO_2 is stored and offloaded at 100 tonnes pressurized tanks (15 bar, -20°C) at refueling stops in Stockholm or Helsinki, it is transferred 10 km to a modular synthesis facility synthesizing annually 20 000 tonnes of methanol.

The route has economic advantage of lower storage requirements that lower capital expenditure on tanks from €2 million for long haul routes to €0.5 million. Nevertheless, the financial profile is dominated by the €15 million retrofit cost and high synthesis expenses (€1.5 million per year, driven by hydrogen costs). As carbon tax savings are €3.7 million and methanol savings are €2.5 million, the annual revenues generated of €6.2 million are insufficient to offset the costs of €9.5 million

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(including capture, transport, maintenance and fuel penalties). Despite these challenges, the NPV of €-13.44 million resulting from this analysis is a promising candidate for pilot projects, as the route has logistical advantages (proximity to synthesis facilities, existing bunkering infrastructure) that favor it in this respect.

There is the prospect of recognition of policy. Subsidizing near hand would make near NPV positive at €1–2 million per annual saving, or €7.4 million per year when a €200/ton carbon tax increase is used to rise savings to €7.4 million/year. Furthermore, projected electrolysis development would enable viability at hydrogen cost reductions to €0.5/kg. Key steps for economic sustainability include policy and cost optimization, as this case study shows that the system is technically feasible.

7. Conclusion

The closed loop methanol fuel system provides the means of maritime decarbonization by enabling 37,000 tonnes of CO_2 emissions savings a year for each vessel, through reusing emissions for the production of renewable methanol fuel. As found in the Net Present Value (NPV) analysis there is a high economic barrier of €13.44 million over a 10 year horizon that stems from €15 million retrofit cost, €4 initial hydrogen cost, and lack of policy support[9]. However, these costs impose a financial burden that exceeds the amount of €3.7 million/year from carbon tax savings and €2.5 million/year (trending at 10% growth annually) of internal methanol production than can be offset within the project timeframe. Having found the technical feasibility on the Stockholm–Helsinki case study based on port calls, the system's economic viability would depend on the availability of external enablers. Further, present value of later-year gains is further further diminished by the 8% discount rate representing the maritime investment risk, highlighting the difficulty of realizing profitability under the current market conditions.

Therefore, necessity of the policy reforms and technological innovation is needed to bridge this economic gap. If captured CO_2 is 'green' under IMO or European Union recognition, this could mean an 'off the carbon tax ledger' at a saving of €7.4 million/year at €200 per ton tax, or €1–2 million/year in subsidy and make the project NPV positive. At the same time, decreases in cost of operation depend critically on improvements in capture efficiency (e.g., PNNL €39/ton target) and hydrogen production (e.g., €0.5/kg through advanced electrolysis). To increase the system, coordinated efforts of stakeholders—shipowners that fund the retrofits, ports that develop CO_2 offloading infrastructure, synthesis operators that invest in modular facilities, and governments that offer incentives—are expected. Aligning with governmental decarbonization goals, for example IMO 2050, 50% emissions reduction, can make this system become one of a cornerstone for sustainable maritime transport if the barriers can be overcome through the interventions.

8. Future work

Real world pilot trials of the closed loop methanol fuel system to rigorous prove cost and performance assumptions are required progressing the Clipper Eris, the Solvang carbon capture test on an LPG carrier. These trials are decisive to adjust the main economic parameters, such as CO_2 capture cost (currently €108/ton) and methanol synthesis expenses for hydrogen price (€ 4 € 104 – € 1/ kg after 10 years). For an example, pilots can confirm if such a capture approach as solid sorbent systems with lower energy penalty withdrawal does not bring a 10% fuel penalty already observed in amine based scrubbers, thus lowering the operational costs by EUR 0.5-1 Million/year[10]. Future development of modular synthesis facilities can also be tested nearby ports and the associated CO_2 transportation logistics can be optimized from €10/ton to €5/ton. Therefore, these trials should include the involvement of ship owners, technology providers and port authorities to achieve scalability and the

DOI: 10.54254/2753-8818/2025.AU24061

integration with existing maritime infrastructure while providing empirical data to improve the estimates used in the NPV models and the investment decisions[11].

Detailed sensitivity analyses to see what types of emerging technologies would potentially allow the economic viability of xPV to take off should be undertaken further. We suggest evaluating technologies such as solid sorbent capture or next generation electrolyzers which may achieve costs for hydrogen around €0.5/kg by 2030 with the use of the tools like MATLAB to determine just what cost thresholds will be positive NPV. For instance, curtailing capture costs down to that same PNNL target of €39/ton would add a whopping €2.5 million/yr to financial bottom lines. Integration with carbon offset markets and maritime Emissions Trading Systems (ETS) also provide revenue opportunities of €50–100/ton CO_2 to offset high capital cost. Because these policies have a large impact on NPV, these analyses should quantify the effect of policy driven revenues on NPV, especially in scenarios with high carbon taxes (€100–300/1000 g), and be used as a guide for the technology development and regulatory advocacy of the stakeholders.

Given the reliance on renewable hydrogen, it is essential to look at the system's environmental integrity and this can be achieved through comprehensive lifecycle assessments (LCAs). These assumptions of green hydrogen production rely on low carbon electricity but variability of mix in grid or upstream emissions from electrolyzer manufacturing can undercut the system's near zero emission claim. Indirect emissions must be considered across the supply chain, where the conclusion of which LCA exercises must be included depends on how the system's true carbon footprint is quantified. Accelerating infrastructure investments, such as port side synthesis facilities, will require collaborative frameworks with industry, policymakers and research institutions to advocate regulatory incentive for recognizing CCU as a decarbonisation strategy. In future work, the closed loop system can be transitioned from a promising concept to a scalable, economically viable solution for the sustainable maritime transport by addressing these research gaps.

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