Zero-Emission Ammonia-Powered Tugboat Power-System Design

By
Inigo Antony
MSc in Sustainable Energy Systems
University of Birmingham and IIT Madras

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Executive Summary

Decarbonizing harbour tug-boats, operating in emission sensitive zones with high energy demands presents as an interesting challenge (1). This work is an attempt to design a zero-emission 1 MW ammonia-powered propulsion system utilizing on-board ammonia cracking to generate hydrogen to power a Low Temperature Proton Exchange Membrane (LT-PEM) fuel cell array. It's a zero-emission system providing alternative to conventional diesel propulsion for tug-boats operating in the harbour. The design is aimed for "first-mover" application that is 'closed to the market', with significant constraints to make it economically viable in the future. The proposed architecture employs a series hybrid configuration comprising ammonia thermal cracking, hydrogen purification, PEM fuel cells and lithium iron phosphate battery storage.

Key design features:

1. **Two-Stage Catalytic Autothermal Ammonia Cracking** using waste hydrogen combustion.
2. **Integrated molecular sieve and PSA purification** delivering high hydrogen purity.
3. **10 x 200 kW fuel cell modules** providing 2 MW gross capacity.
4. **Iron-phosphate battery** for startup operations and peak shaving.
5. **Catalytic burner** for hydrogen combustion for heating the cracker.

The highly complex and optimized system achieves 22.8% ammonia-to-propeller efficiency (LHV basis), consuming 890 kg/h ammonia to deliver 1 MW net propulsion power. The design achieves a 12-hour operational endurance at full load, overcoming the energy density limits of battery-electric alternatives. The "crack-then-consume" approach eliminates the need for high pressure storage related risks leveraging the energy density and established infrastructure of ammonia systems. The system archives zero local emissions with negligible amount of NOx from catalytic hydrogen combustion.

Even though the proposed system's efficiency is lower (~23%) than diesel (~42%) system, it enables zero emission, low-noise operation with potential for zero lifecycle CO_2 emissions. At current green ammonia pricing ($900/tonne), the operating cost is $2.6M compared to $0.81M for diesel at 3.24 times premium. However, lifecycle CO_2 emission is reduced to zero providing incentive for pursuing ammonia powered propulsion and potential adoption with improved carbon tax rates (by policy pushes) and reduction in green ammonia prices (driven by innovation and scaling).

1. Introduction

1.1 Background and Motivation

In the aspect of tackling climate change, curtailment of greenhouse gases (GHG) is the need of the hour. The shipping industry contributes around 2% of the global emissions and is expected to increase in the future (2,3). The International Maritime Organization (IMO) has laid out mandates to achieve net-zero emissions for shipping by 2050 (4). The IMO plans to employ financial incentives to ships and boats with zero-emission capabilities and several other regulations (California - 2030, the European Union - 2035, and Singapore - 2040) pushing for zero-emission technologies (5–7). Moreover, ports are set to become zero-emission zones which poses great engineering challenges and a need for zero-emission propulsion technologies (8). This calls for reduction of emissions from harbour vessels such as tugboats as they emit large amounts of carbon and significantly degrade local air quality in port cities (1). Decarbonization of the power system in tugboats is a great engineering challenge given the long operational hours and high power required.

Among the zero-emission fuels, hydrogen (H_2) and ammonia (NH_3) have the potential to replace diesel for propulsion. But gaseous hydrogen suffers from poor volumetric density and liquid hydrogen requires a lot of new infrastructure and is very costly (9,10). In contrast, ammonia offers compelling advantages for maritime applications. Its high volumetric energy density (12.7 MJ/L vs 8.5 MJ/L for liquid hydrogen), established infrastructure, and ability to be synthesised from renewable electricity makes it particularly suitable for vessels with constrained fuel storage. But direct ammonia combustion is a relatively nascent technology and produces NOx emissions which makes it unsuitable for port operations (11,12). A more complex but viable method would be to crack ammonia on-board and use it to power fuel cells enabling true zero-emission power system (13). Amogy successfully demonstrated a zero-carbon emission ammonia powered propulsion system by retro-fitting an old tug-boat with ammonia cracker paired with Ballard FCwave fuel cell system (14,15).

Figure 1: Amogy's NH_3 Kraken Tug-boat

But the technology used is ambiguous and it is not zero-emission system but rather zero-carbon emission system (with NOx emissions). In the aspect of on-board cracking, high temperature (700 °C – 1000 °C) is required to crack the ammonia and a suitable catalyst (like Ruthenium or Nickel) is required which my contribute to the cost and complexity of the process. Eluwah and Fennell (2024) designed a novel carbon-free ammonia-to-hydrogen process using hybrid air-volt ammonia cracker (HAVAC) (16).

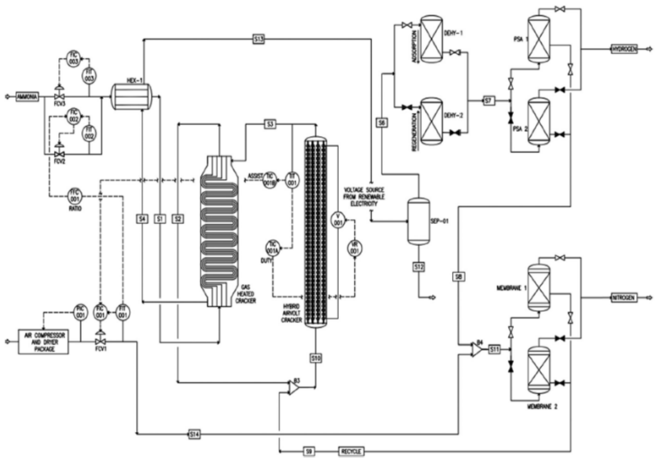

Figure 2: Schematic of the HAVAC system (16).

The process uses a Gas Heating Chamber (GHC) to use the waste heat produced from hydrogen and ammonia combustion to increase efficiency. Moreover, the process allows for operating in autothermal mode (combustion of ammonia and hydrogen), electric mode and hybrid mode (electric and autothermal). The produced hydrogen is purified to fuel cell grade quality using micro sieves and Pressure Swing Absorption (PSA) system (17). This process can be leveraged for designing on-board cracking with high efficiency and portability. This report is an attempt to present ammonia-to-propulsion system with detailed design, emissions and cost calculations.

1.2 Objectives

This report proposes a design for ammonia-to-propulsion system for harbour tug-boats with the following specifications:

- Net propulsion power: 1 MW at propeller shaft
- Operational endurance: 12 hours without refuelling
- Emissions target: Zero local emissions (NOx, SOx, PM, CO_2)
- Power system: On-board ammonia cracking with fuel cell module

The analysis details the technical design, economic evaluation, and lifecycle carbon assessment using green ammonia as fuel.

1.3 Design Overview

The propulsion system employs a series hybrid architecture where ammonia serves as the primary energy carrier. Liquid ammonia is vaporised, thermally cracked to hydrogen and nitrogen, purified to fuel cell grade, and converted to electricity in PEM fuel cells. A lithium iron phosphate battery provides peak shaving, cold start capability, and regenerative braking energy storage.

The system is designed around autothermal operation, where waste hydrogen streams (PSA tail gas and fuel cell anode purge) are combusted to provide cracking heat. This approach eliminates the huge electrical load associated with electric heating (electric mode of HAVAC) and avoids using NH_3 combustion that produces NOx emissions. The result is a near-zero emissions system achieved through catalytic hydrogen combustion (18). The startup is facilitated by the battery through resistive heating which partially converts the ammonia to hydrogen followed by ramping up to full autothermal conversion.

2. Project Display

2.1 Design Overview and Components

In summary, the ammonia-powered propulsion system converts liquid ammonia to electrical power through a sequential process: ammonia vaporisation, catalytic cracking to hydrogen/nitrogen, purification to fuel cell grade hydrogen, electrochemical conversion in PEM fuel cells, that powers the propulsion motor. Waste hydrogen from PSA tail gas and anode gas purge is burnt in the combustor/catalytic burner providing continuous heat for autothermal cracker operation (19). The battery does the crucial role of starting the cracking process through partial conversion by electric heating of the HAVAC beds and powering all the support systems like vaporizer (electric heating), compressors, control systems, pumps, etc. The process is then ramped up to run on waste hydrogen.

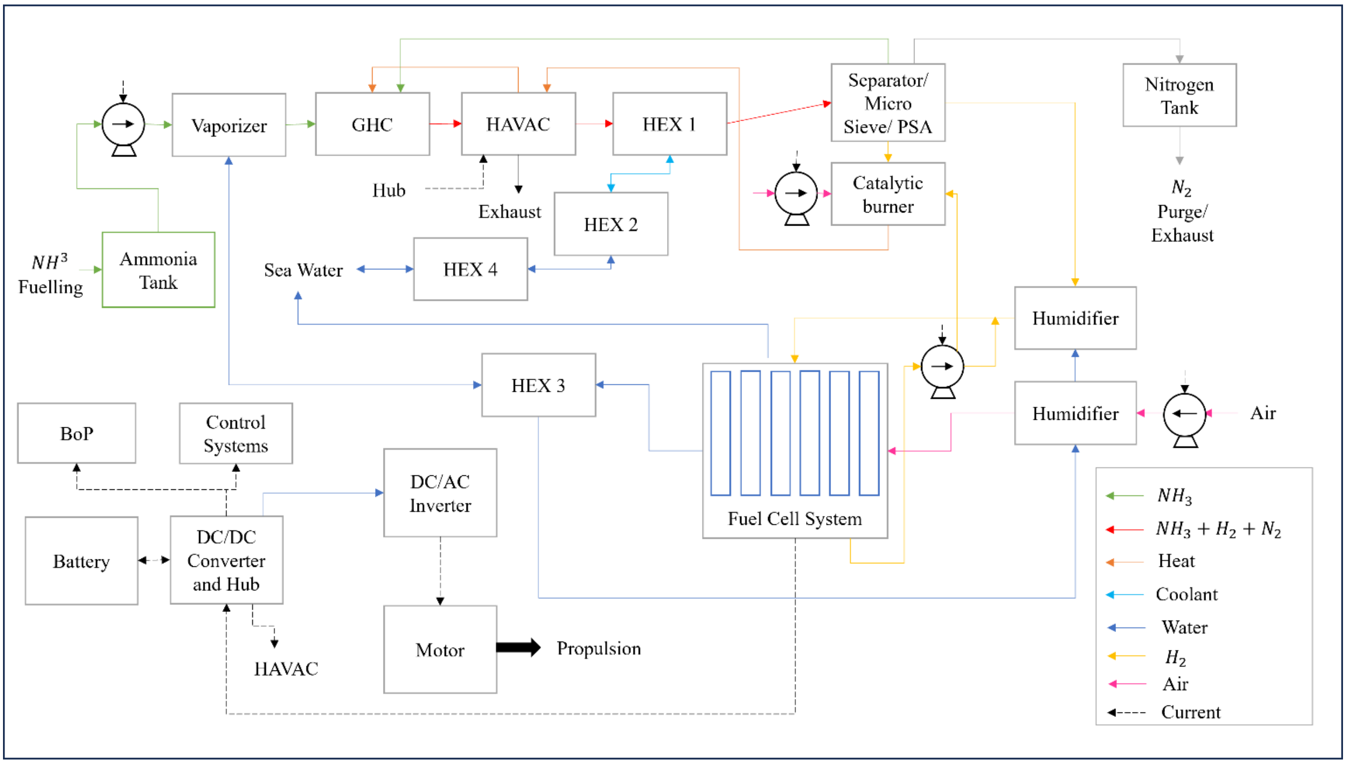

Figure 3: Block diagram of ammonia powered tug boat power system.

2.2 Working

The process starts from the battery powering the resistance heaters in vaporizer and HAVAC along with the pumps and other BoP (Balance of Plant) components (pumps, compressors, blowers, etc). The HAVAC and the vaporizer are heated and the cryogenic pumps send ammonia (at -33 C) from the tank through the vaporizer, that vaporizes the ammonia and then it passes through the HAVAC (lined with Ruthenium catalyst) which is brought to around 400 °C and the ammonia gets partially oxidized (~50%) (16,20). The hot products (NH_3+H_2+N_2) pass through the GHC transferring heat to the fresh ammonia entering and a multi stage heat exchanger cooling system (HEX 1 and HEX 2) that cools the products down to 40 °C (21). Then the product gas enters the purification modules consisting of separators, micro-sieve beds and PSA beds (13,16). The purified hydrogen is then passed through the humidifiers and enters the fuel cell module (along with air). The remaining tail gas (only 75% purified), is sent to the catalytic burner that burns the hydrogen and ammonia to produce high grade heat (22).

Simultaneously, hydrogen passed to the fuel cell is electrochemically converted (at 50% electrical efficiency) to produce electrical power (and heat) which is routed through a DC/DC converter to an electrical hub which then sends it to the motor via an inverter (AC/DC) to power the motor (23). The fuel utilization of the fuel cell system is only 85%, operating in partial anode recirculation mode (24). The partial anode recirculation mode operates by sending part of the excess hydrogen back to the fuel cell while some is routed to the catalytic burner (25). The heat from the catalytic burner is transferred to the HAVAC system which then starts to heat up to higher temperatures approaching (700 °C) and switching to autothermal mode. The battery connected in parallel to the fuel cell module through the electrical hub and DC/DC converter, stops discharging and starts to charge from the fuel cell power output. The battery also does peak shaving/filling operation when sudden power fluctuations arise. The control systems and the BoP components are connected to the battery and fuel cells via the electrical hub (26). The waste heat from the fuel cell module is used in the vaporizer and the excess is rejected to the surroundings. The heat exchanger from HAVAC system handles high heat and therefore has 2 stages (HEX 1 and HEX 2) with corresponding coolant (thermal oil, glycol, etc) (27). The excess heat is rejected to the surrounding using sea water loop. The combustion products from the catalytic converter (H_2O, N_2 and small amount of NOx) is let out through an exhaust after exchanging heat to the HAVAC (28).

Table 1: Component list and specifications

Component	Specification	Efficiency	Notes
NH_3 Storage	18.0 m³, 13 tonne capacity	-	-33 °C, 1 bar
NH_3 Pump	Cryogenic pump, 890 kg/h capacity	-	-33 °C inlet
Vaporiser	Shell-and-tube heat exchanger (FC coolant heated) with electric heating capability	-	-33 °C to 25 °C, uses FC waste heat
GHC	Gas Heated Catalytic reactor (Ru/Al_2O_3 catalyst, waste heat mode)	45% conversion	~600 °C
HAVAC	Autothermal Ammonia Cracker (Ru/Al_2O_3, H_2 combustion heated/Electric)	99.5% total	~700 °C, 688 kW heat required
Electric Heater	Resistance heater for startup	99%	Startup only (0 kW at steady state)
Combustor/ Catalytic Burner	Pt/Pd catalyst, H_2 combustion for cracker heat, 54.2 kg/h H_2 capacity	90%	~800 °C outlet, 1,695 kW heat

Component	Specification	Efficiency	Notes
Molecular Sieve	Zeolite adsorbent beds	>99.9% NH_3 removal	~40 °C, removes residual NH_3
PSA System	Pressure Swing Adsorption for producing fuel cell grade hydrogen purity	~75% H_2 recovery	~40 °C, high H_2 purity
Fuel Cells	10 x 200 kW PEM modules (2 MW total capacity)	50% (electrical)	~80 °C, ~2 bar, 1,660 kW gross output
Anode Recirculation Blower	Ejector + blower combination for H_2 recirculation	-	λ=1.3, 85%
Heat Exchanger 1,2	Product gas cooler (between HAVAC outlet and PSA inlet), Thermal oils and water	-	~700 °C to 40 °C
Heat Exchanger 3	FC coolant to vaporiser	-	75 °C coolant, vaporises liquid NH_3
Heat Exchanger 4	Seawater heat rejection	-	Rejects ~1,270 kW excess FC heat
Cathode Air Compressor	For fuel cell operation (λ = 2)	-	-
Burner Air Blower	Blower for combustor air supply	-	-
Humidifiers	Membrane humidifier for cathode air (enthalpy wheel backup)	-	Maintains 80-100% RH at FC cathode
FC Cooling Pumps	Variable speed pumps (deionised water/glycol)	-	maintains FC at 80 °C
Seawater Pump	Pump for heat rejection loop	-	-
Control Systems	For power distribution across various components	-	-
Battery System	600 kWh $LiFePO_4$ (lithium iron phosphate)	95% round-trip	Startup, peak shaving, emergency backup
DC/DC Converter	Converts DC voltage from fuel cell and battery to required voltage	97%	-
Inverter	Inverts the DC voltage to AC for powering the motor	95%	-
Propulsion Motor	Propulsion motor, 1 MW rated	98%	-
N_2 Purge System	Nitrogen storage and distribution for safety purging	-	

2.3 Design Approach

The design was inspired from Amogy's Tug boat design and Eluwah et.al paper on hybrid air-volt ammonia cracker (HAVAC) system (16,29). The system design followed a backward calculation methodology, starting by fixing the output requirement (1 MW propulsion, from Amogy's design) and working upstream through each subsystem to determine component sizes. This approach ensures that every component is correctly sized to meet the demand while accounting for losses at each conversion step.

The design process comprised of five steps:

1. Electrical power module sizing from propeller to fuel cell (from LHV and efficiency)
2. Hydrogen flow rate determination based on fuel cell requirements
3. Ammonia feed rate calculation from cracking stoichiometry
4. Thermal integration analysis to verify autothermal feasibility

5. Storage and support system sizing (approximated to certain degree)
6. Energy and mass balance checks for validation.

The assumptions made and constraints in this design:

1. The volume and weight of most components is ambiguous and therefore is not considered in this calculation for simplicity.
2. The load of Balance of Plant (BoP) is approximated for simplicity of calculation.
3. The CAPEX of the system is not considered in the calculations (CAPEX of this system is expected to be large considering the complexity and cost of the sub systems).
4. The system is "close-to-market" with expected use case in a decade or so betting on increased carbon prices, cheaper green ammonia prices and financial subsidies in the future.

3. Project Analysis

3.1 Fuel Cell Power Requirement

For propeller shaft power of 1 MW, we can reverse calculate the fuel cell requirement after knowing the efficiencies of the intermediate conversion steps from each component. Standard values for the efficiencies of motor, inverter, and DC/DC converter are assumed. The battery load is calculated based on power requirement until the cracker is warmed up which can be estimated to be approximately 20 minutes. For 1000 kW output for 20 minutes, 333 kWh is required. 600 kWh battery pack is utilized (at ~50% margin) for backup power and peak shaving operations. And BoP load is assumed to be 30% of the total fuel cell output power. And 50 kW electric load from fuel cell is taken for charging the battery.

Table 2: Power requirement calculation

Component	Efficiency	Output (kW)	Input (kW)
Propeller shaft (target)	-	1,000	-
Electric motor (98%)	98%	1,000	1,020
Inverter (95%)	95%	1,020	1,074
Battery (+ 50 kW)	-	1,074	1,124
DC/DC converter (97%)	97%	1,124	1,160
Balance of Plant (30%)	-	-	+500
FC gross output required	-	-	**1,660**

The fuel cell capacity is sized for approximately 80% utilisation: 1,660 kW / 0.80 = 2,075 kW, rounded to 10 modules of 200 kW each (2,000 kW total). This provides 83% utilisation with enough margin for degradation and failures.

3.2 Hydrogen Requirements

At 50% fuel cell efficiency (electric) and 33.33 kWh/kg hydrogen LHV, hydrogen consumption is 99.6 kg/h. With 85% fuel utilisation in recirculation mode, fresh hydrogen feed from PSA is 117.2 kg/h.

3.3 Ammonia Feed Rate

With 75% PSA recovery and 99.5% cracker conversion, hydrogen from cracker is 156.2 kg/h. From stoichiometry ($2NH_3 \rightarrow 3H_2 + N_2$), ammonia feed rate is 890 kg/h.

3.4 Ammonia Tank Sizing

For 12-hour operation and 890 kg/hr, the total ammonia requirement is 10,680 kg. With 15 % buffer storage the total ammonia stored is 12,282 kg. The tank size can be approximated to 13 tonnes.

3.5 Process Flow Calculations

Table 3: Process flow calculations

Stream	Flow (kg/h)	H_2	N_2	NH_3	T (°C)
NH_3 Feed	890	-	-	890	-33
Cracker Outlet	890	156.2	729.4	4.4	700
PSA H_2 Product	117.2	117.2	trace	-	40
PSA Tail Gas	768.4	39.0	729.4	-	40
FC Anode Inlet	129.5	129.5	trace	-	80
Anode Purge (continuous)	17.5	17.5	trace	-	80
To Combustor (total)	56.5	56.5	-	-	-

3.6 H_2 Anode Recirculation Mass Balance

The recirculation of H_2 is done to achieve better fuel utilization and some hydrogen is purged to burn in the catalytic burner. The calculation doesn't account for startup scenarios during which hydrogen is supplied according to assumed stoichiometry (λ=1.3) (30).

Table 4: Anode recirculation mass balance calculation

Parameter	Value
Fresh H_2 feed (from PSA)	117.2 kg/h
Recycled H_2 (from anode)	12.3 kg/h
H_2 at anode inlet (λ = 1.3)	129.5 kg/h
H_2 consumed (reaction)	99.6 kg/h
Anode exhaust	29.9 kg/h
Continuous purge to burner	**17.5 kg/h**

3.7 Autothermal Heat Requirement

The autothermal operation is verified by comparing heat available from hydrogen combustion with heat required for cracking. Theoretically, heat required for cracking 890 kg/hr of ammonia is 668 KW at (using 46 kJ/mol). The sensible heat required is provided but the hot gas from the cracker. Heat from hydrogen combustion in the burner at 90% efficiency is 1,695 kW from 56.6 kg/hr of hydrogen (39 kg/hr from tail gas and 17.5 kg/hr from anode purge).

Table 5: Autothermal heat requirement calculations

Parameter	Value
H_2 to combustor (PSA tail + anode purge)	56.5 kg/h
Combustion energy (LHV)	1,883 kW
Heat available (90% burner efficiency)	1,695 kW
Cracker heat requirement (reaction)	668 kW
Heat losses (~10%)	67 kW
Surplus heat	**960 kW**

3.8 Energy Balance

The energy balance is calculated by from NH_3 LHV (5.17 kWh/kg) input power and subtracting for each process. This acts as a sanity check for the whole design process. For the total input ammonia feed of 890 kg, the calculated input power is ~4600 KW. Fuel cell waste heat is 50% of the rated power (1,660 kW). Electronic losses (from inverter, DC/DC converter and motor) are calculated to be 88 KW. Excess heat from fuel cell module, heat rejected before purification and other excess heat amounts to 819 kW.

Table 6: Energy balance calculation

Energy Stream	Power (kW)	Percentage
Input: NH_3 (LHV)	**4,600**	**100%**
Propulsion + Battery	1,050	22.8%
FC Waste Heat	1,660	36.1%
Combustor Excess Heat	983	21.4%
Electronics Losses	88	1.9%
Exhaust and Other	819	17.8%
Total Output	**4,600**	**100%**

3.9 System efficiency

The overall system efficiency is defined by the ratio of useful mechanical output to chemical energy input:

$$\eta_{\ system} = P_{useful} / E_{input} = (P_{propulsion} + P_{battery}) / (m_{NH_3} \times LHV_{NH_3})$$

$$\eta_{\ system} = 1{,}050 / 4{,}600 = 0.228 = 22.8\% \approx 23\%$$

4. Economic Analysis

4.1 Operating Expenditure

Annual operating costs are calculated based on 3,000 operating hours per year (250 days x 12 hours). Green ammonia fuel costs are calculated using $900/tonne as estimated price (at 890 kg/hr consumption)(31). Annual diesel costs are calculated using $800/tonne (at 220 kg/h consumption) (32). For diesel power system, carbon costs are taken at $100/tonne of CO_2 for 3.2 tonnes of CO_2 produced per tonne of diesel (33). Other costs like maintenance, labour and insurance costs are estimated to be 10% of the fuel costs.

Table 7: OPEX calculations

Cost Component	Green NH_3	Diesel Baseline
Fuel cost	$2,400,000	$528,000
Carbon cost ($100/t CO_2)	$0	$211,000
Other costs (10%)	$240,000	$74,000
Total annual OPEX	**$2,640,000 (3.24x premium)**	**$813,000**

5. Carbon Emission Analysis

5.1 Local Emissions

The fuel cell propulsion system achieves zero local emissions of CO_2, SOx, and particulate matter at point of use. NOx emissions are very limited coming only from the catalytic hydrogen combustor which is much better compared typical of stoichiometric ammonia combustion engines (34).

5.2 Lifecycle Emissions Comparison

From the lifecycle emission calculations, it's evident that usage of grey ammonia is worse than using diesel. But green and blue ammonia show much reduced emissions (35).

Table 8: Lifecycle Emission Calculations

Fuel Pathway	CO_2 (t/yr)	Emissions vs Diesel	Carbon Cost
Diesel (baseline)	2,110	-	$211,000
Grey NH_3 (@1.9 CO_2/t)	5,070	+141%	$507,000
Blue NH_3 (@0.2 CO_2/t)	534	-75%	$53,400
Green NH_3	**0**	**-100%**	**$0**

6. Summary

This design demonstrates an ammonia-to-propulsion system achieving 23% overall efficiency proving the feasibility of integrated ammonia cracking and PEM fuel cell systems. The system leverages the energy density of ammonia and waste heat from cracking and fuel cell system to achieve good performance. The design envisions the future of zero-emission propulsion with renewable fuels and infrastructure. But, key design metric like volume, weight and flow rate can be optimized further.

6.2 Key Design Features

1. On-board autothermal ammonia cracking with waste heat recovery achieving 99.5% conversion efficiency.
2. Molecular sieve beds and PSA absorption provide high purity hydrogen to the fuel cell module.
3. 2 MW FC stack (10 modules at 83% utilisation)
4. Partial Anode recirculation and PSA tail gas are used for providing continuous combustor fuel
5. Catalytic burner converts excess H_2 to provide heat for ammonia cracking
6. 600 kWh battery for startup and peak shaving

6.3 Environmental Performance

The system achieves zero local emissions (CO_2, SOx, PM) with negligible NOx. Using green ammonia enables complete lifecycle decarbonisation, while blue ammonia provides 75% reduction compared to diesel baseline.

6.4 Economic Outlook

Annual OPEX of $2.6 million represents a 3.24x premium over diesel. Cost competitiveness is projected for 2035-2040 as green ammonia prices decrease and carbon pricing increases.

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