Ammonia to Hydrogen Conversion System for Maritime Transport

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Process Design

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Abstract

This paper presents a traceable conceptual design of a 50,000 DWT cargo ship that stores refrigerated ammonia and converts it onboard to hydrogen for PEM fuel-cell electric propulsion. The contribution is a coupled mass, energy, equipment and marine-integration basis rather than an isolated process block. The design closes the selected 6,000 nmi voyage with 10 MW average shaft demand, 1 MW average auxiliaries, 55% net fuel-cell efficiency, 90% effective cracking and 95% hydrogen recovery. The resulting requirement is 257.1 t of hydrogen and 1,704 t of ammonia; a 2,500 t usable inventory is retained for reserve, degradation and operations.

The central modelling decision is to include auxiliary electrical demand explicitly. The propulsion shaft is 10 MW, while the fuel-cell plant supplies 11 MW average electrical output.

Keywords

Ammonia fuel; hydrogen cracking; PEM fuel cell; electric propulsion; cargo ship; marine energy system; conceptual design; pre-FEED.

Nomenclature and units

Symbol	Definition	Unit
D	Voyage distance	nmi
V	Ship speed	kn
t	Voyage time	h
P_{shaft}	Shaft demand	MW
P_{aux}	Auxiliary demand	MW
η_{FC}	Net fuel-cell efficiency	–
m_{H2}	Delivered hydrogen mass	t
m_{NH3}	Consumed ammonia mass	t
LHV	Lower heating value	MJ/kg

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Chapter 1

Introduction and research question

The design question is: can a medium-size cargo ship carry enough ammonia and convert it onboard to fuel-cell-grade hydrogen for a representative ocean voyage while maintaining redundancy, safety and a credible marine arrangement? The answer requires more than a chemical reaction balance. It requires an explicit voyage, hull and propulsion basis, tank inventory, thermal duty, auxiliary load, control philosophy and verification plan.

Chapter 2

Mission, vessel and cargo basis

2.1 Purpose, scope and design maturity

This report develops a conceptual design for a cargo ship that carries ammonia as an energy vector and converts it onboard into hydrogen for fuel-cell propulsion. It expands the design basis into a traceable technical memorandum with a single author, an explicit mission basis, and a clear separation between calculated values and engineering assumptions. The document is intentionally positioned between a university process-design project and a pre-FEED study. It is detailed enough to expose mass, energy, equipment and safety interactions, but it does not replace class approval, CFD, structural calculation, vendor guarantees or a shipyard design spiral. Every important result is therefore accompanied by the assumption that controls it and by the next validation step required. The vessel basis is deliberately stated as a chain of auditable assumptions. Deadweight is treated as a cargo and consumables constraint, while the energy model is driven by shaft power and hotel load rather than by a nominal engine rating. This distinction matters because the chemical plant, refrigeration system, ventilation fans and pumps remain live during the voyage even when the propeller load changes. The design therefore separates installed capacity, average operating demand and reserve capacity at every interface. The resulting arrangement is a systems-engineering compromise. The forward holds remain available for the commercial cargo, the ammonia tanks are located within a segregated machinery zone, and the conversion plant is placed close to both the tanks and the fuel-cell room. Shorter hydrogen lines reduce inventory and pressure-drop penalties, while a physical separation between ammonia and hydrogen zones limits the consequences of a single release. These are arrangement decisions that cannot be recovered later by adjusting a process spreadsheet.

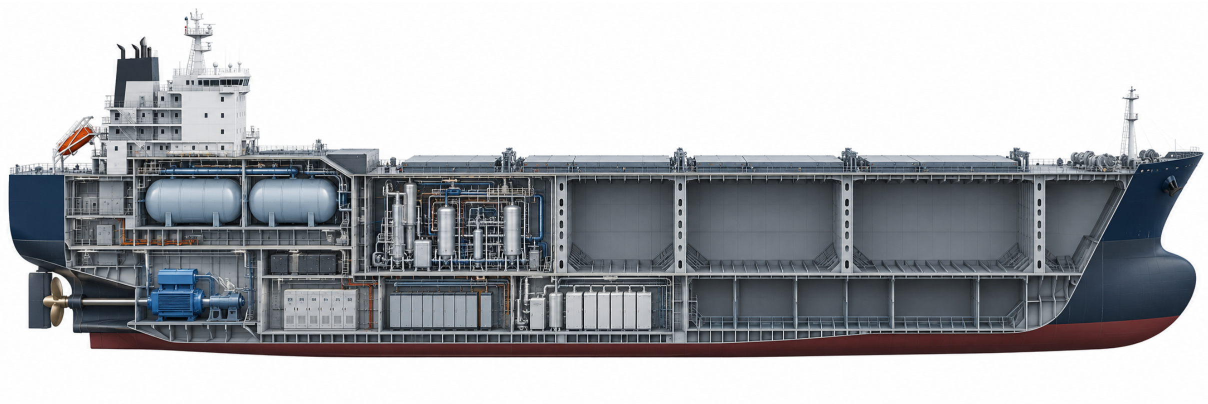

Figure 2.1: Conceptual longitudinal arrangement of the cargo, ammonia, conversion and electric-propulsion zones.

Table 2.1: Design values for purpose, scope and design maturity

Item	Basis or value	Interpretation
Design intent	Integrated ammonia logistics, cracking and electric propulsion	Conceptual pre-FEED
Author	Saul Moreno	Technical design report
Primary deliverable	A coherent vessel and onboard energy system	Academic technical report
Excluded	Class approval, fabrication drawings, certified stability	Future design stage

2.2 Executive summary

The proposed vessel is a 50,000 DWT ammonia-ready cargo ship with a preliminary length overall of 100 m, beam of 17 m, design draft of 8.5 m and service speed of 14 kn. Two segregated refrigerated ammonia tanks provide 2,500 t of usable inventory. Two catalytic cracker trains convert ammonia to a hydrogen-rich gas, and two 6 MW PEM fuel-cell trains provide approximately 11 MW net electrical output for a 10 MW shaft demand plus auxiliaries. On the selected 6,000 nmi voyage, the ship sails for 428.6 h, or 17.9 days. A 10 MW average shaft demand plus a 1 MW average auxiliary load corresponds to 4,714 MWh of delivered electrical energy. At 55% net fuel-cell efficiency, this requires 257.1 t of hydrogen. With 90% effective cracking and 95% purification yield, the calculated ammonia consumption is 1,704 t. The selected 2,500 t inventory therefore includes a substantial operational reserve.

Table 2.2: Design values for executive summary

Item	Basis or value	Interpretation
Vessel concept	50,000 DWT cargo ship	100 m x 17 m x 8.5 m
Voyage	6,000 nmi at 14 kn	428.6 h
Propulsion	Two 6 MW PEM trains	10 MW shaft + 1 MW auxiliaries
NH3 consumption	Calculated voyage requirement	1,704 t
Installed inventory	Two Type-C tanks	2,500 t usable

2.3 Mission profile and operating modes

The design mission is a representative ocean passage of 6,000 nautical miles. It is not tied to a named port pair; instead it provides a repeatable basis for comparing equipment and fuel demand. The ship is assumed to cruise at constant 14 kn for the main passage, with additional energy allowances for acceleration, manoeuvring, hotel services, weather and port operation. Four operating modes are defined. In harbour, shore power supports hotel loads and the cracker remains in warm standby. During departure, both fuel-cell trains are available and the ammonia feed is ramped gradually. At sea, one train can carry reduced load while the second remains available for redundancy. During emergency shutdown, ammonia isolation valves close, the stacks are purged with nitrogen, and a small battery maintains essential control and steering loads.

Table 2.3: Design values for mission profile and operating modes

Item	Basis or value	Interpretation
Harbour	Hotel load, shore power, warm standby	0.8 MW electric
Departure	Ramp propulsion and auxiliaries	2 to 11 MW
Cruise	Normal passage, N plus 1 availability	10 MW shaft + 1 MW auxiliaries
Emergency	Isolate NH3, retain steering and control	Battery-backed

2.4 Design basis and notation

The report uses SI units except for nautical miles, knots and tonnes, which are conventional in marine design. Gas flows are reported in kmol/h or Nm3/h. The normal volume reference is 0 C and 1 atm, with 22.414 Nm3 per kmol of ideal gas. Lower heating values are used for fuel accounting, and efficiencies are stated on a net delivered basis unless explicitly labelled otherwise. The main chemical basis is the ideal cracking reaction 2 NH3 -> N2 + 3 H2. The mass fraction of hydrogen in ammonia is therefore 3 kg H2 per 17 kg NH3, or 17.65% before conversion losses. The actual design yield is reduced by catalyst conversion, purge losses, hydrogen purification, stack degradation and operating reserve.

Table 2.4: Design values for design basis and notation

Item	Basis or value	Interpretation
Gas reference	0 C, 1 atm	22.414 Nm3/kmol
NH3 molecular mass	17 kg/kmol	Basis for mass balance
H2 molecular mass	2 kg/kmol	3 mol H2 per 2 mol NH3
NH3 hydrogen fraction	3/17	17.65 wt% theoretical
Power basis	Net electrical output	After auxiliaries

Chapter 3

Ammonia storage and cargo handling

3.1 Hull dimensions and arrangement

The preliminary hull envelope is selected to support a protected midship ammonia zone, machinery spaces aft, accommodation and bridge forward, and sufficient separation between hazardous and non-hazardous areas. The 100 m length is not presented as an optimised hydrodynamic result; it is a coherent first sizing that leaves room for tanks, cargo holds, cracker modules and a conventional stern propulsion arrangement. The arrangement places the ammonia tanks low and near the longitudinal centre of gravity, reducing trim sensitivity as fuel is consumed. The cracker and fuel-cell rooms are located in separate ventilated machinery spaces with short hydrogen pipe runs. Cargo holds remain physically separated from the energy plant so that the ship retains a useful commercial cargo function even when the energy system is under maintenance.

Table 3.1: Design values for hull dimensions and arrangement

Item	Basis or value	Interpretation
Length overall	100 m	Preliminary hull envelope
Beam	17 m	Initial stability and layout basis
Design draft	8.5 m	Displacement estimate basis
Machinery zone	Aft third	Short shaft line
NH3 zone	Protected midship	Low CG and segregation

3.2 Displacement, deadweight and lightweight estimate

A first displacement check is required before a cargo capacity claim can be made. For this conceptual design, deadweight is taken as 50,000 t and lightweight as 18,500 t, giving a design displacement of 68,500 t at the selected draft. This is a deliberately transparent estimate; a lines plan and hydrostatic model would be required to replace it. The ammonia inventory is treated as a consumable deadweight component. The selected tanks contain 2,500 t of usable liquid plus tank structure, insulation, pipework and safety systems. The cargo, fuel and ballast schedule must be solved together because filling the ammonia tanks changes draft, trim, propeller immersion and longitudinal strength.

Table 3.2: Design values for displacement, deadweight and lightweight estimate

Item	Basis or value	Interpretation
Deadweight	50,000 t	Cargo, stores, liquids and crew
Lightweight	18,500 t	Hull, machinery and permanent systems
Displacement	68,500 t	Conceptual full-load basis
NH3 liquid	2,500 t	Usable energy inventory
Design margin	10% on lightweight	Uncertainty allowance

3.3 Cargo capacity and tank allocation

The energy system is sized around ammonia inventory rather than hydrogen storage. This avoids the large volume penalty of compressed hydrogen tanks and places the principal containment challenge in refrigerated liquid ammonia storage. Two equal tanks are selected so that one tank can be isolated for inspection while the other maintains limited operation. A 2,500 t usable inventory corresponds to approximately 2,941 m3 at a liquid density of 850 kg/m3. Allowing for an 80% maximum liquid fill and a 10% geometric allowance for internal structure, the gross tank volume is approximately 4,085 m3. Two tanks of about 2,040 m3 gross volume are therefore a reasonable first layout target.

Table 3.3: Design values for cargo capacity and tank allocation

Item	Basis or value	Interpretation
NH3 usable mass	2,500 t	Operating inventory
Liquid density	850 kg/m3	Conceptual at refrigerated condition
Liquid volume	2,500 / 0.85	2,941 m3
Fill fraction	80% liquid maximum	Vapour space and expansion
Gross tank volume	2,941 / 0.80 / 0.90	Approximately 4,085 m3

3.4 Ammonia thermodynamics and storage condition

Refrigerated ammonia storage near atmospheric pressure is selected to reduce tank wall thickness and avoid the very high pressure of fully pressurised storage. The reference temperature is approximately -33 C, with pressure controlled near atmospheric conditions. Boil-off is managed by reliquefaction, controlled consumption in the cracker, or a dedicated emergency treatment path. The refrigeration system must handle heat ingress, pump heat, loading transients and solar exposure. The conceptual report does not claim a final refrigeration duty; instead it identifies the duty as a design gate. The tank insulation, relief valves, vapour return connection and emergency vent mast are part of the containment system and must be developed together.

Table 3.4: Design values for ammonia thermodynamics and storage condition

Item	Basis or value	Interpretation
Storage mode	Refrigerated liquid	Near atmospheric pressure
Reference temperature	-33 C	Conceptual saturation condition
Tank fill	80% maximum liquid	Expansion and vapour space
Boil-off strategy	Reliquefaction or controlled use	No routine venting
Validation	Thermal transient model	Tank vendor and class review

3.5 Type-C tank concept

Type-C pressure-vessel tanks are selected as a conservative conceptual basis because they provide independent containment and a clear inspection philosophy. The final tank type could change after a shipyard comparison with membrane containment or larger independent tanks. The report therefore treats Type-C as a design choice, not a regulatory conclusion. Each tank requires pressure relief, level measurement, temperature measurement, isolation valves, vapour return, drain and sampling connections. Double-wall piping is used outside the tank boundary, and the tank room is separated from accommodation. The structural support system must allow thermal contraction while transferring sloshing and collision loads into the hull.

Table 3.5: Design values for type-c tank concept

Item	Basis or value	Interpretation
Tank count	2	Isolation and redundancy
Relief philosophy	Independent relief paths	Overpressure protection
Instrumentation	Level, pressure, temperature	Continuous monitoring
Pipework	Double-wall in hazardous zones	Leak detection
Structural check	Sloshing and thermal contraction	Detailed design gate

3.6 Cargo transfer and bunkering

Bunkering is assumed to occur while the ship is alongside. A closed vapour-return connection limits ammonia release and reduces pressure rise in the receiving tank. Transfer rate is selected to complete loading without excessive thermal stratification; the final rate depends on terminal equipment and the tank heat balance. The transfer procedure includes line cool-down, leak test, inerting, connection verification, controlled fill, vapour return and line drain-down. Emergency release couplings and remotely operated isolation valves limit the quantity released if the ship moves unexpectedly. These steps are operational controls as important as the tank itself.

Table 3.6: Design values for cargo transfer and bunkering

Item	Basis or value	Interpretation
Transfer medium	Refrigerated liquid NH3	Closed vapour return
Transient flow	120 t/h design pump rate	Conceptual maximum
Cool-down	Controlled pre-cooling	Avoid thermal shock
Emergency	Remote isolation and dry-break	Limit release
Records	Mass, temperature, pressure	Bunker custody data

Chapter 4

Chemical conversion process

4.1 Overall process architecture

The onboard process begins with liquid ammonia pumping and vaporisation. The vapour is heated to cracker inlet conditions and split between two catalytic reactors. The cracked gas is cooled, condensed water is removed, and residual ammonia is captured before hydrogen reaches the fuel-cell stacks. Nitrogen is vented only through a controlled treatment path. The process is deliberately modular. Each cracker train is sized for approximately 60% of maximum demand, giving N plus 1 operation at reduced load. The purifier is duplicated or arranged with bypass capability. This architecture reduces the consequence of a single failure and allows maintenance while the ship remains manoeuvrable. The cracker is sized from the voyage average rather than from a nominal peak flow. A two-train configuration is selected so that one train can carry the reduced mission load during maintenance or a controlled trip of the other train. Each train includes feed vaporisation, preheating, catalytic decomposition, heat recovery, hydrogen polishing and a controlled purge. The process boundary ends at fuel-cell-grade hydrogen, so ammonia slip is treated as a separation and monitoring problem rather than assumed to be zero. Thermal integration is central to the concept. The cracker duty is small compared with the fuel-cell reject heat, but it is at a higher temperature level and cannot be satisfied by any arbitrary cooling loop. The proposed hierarchy uses recovered high-temperature heat first, an electric trim heater second and a dedicated low-carbon auxiliary source for cold start. This preserves the energy balance during start-up, manoeuvring and low-load operation.

Figure 4.1: Conceptual equipment-room view of the redundant ammonia-cracking and hydrogen-purification trains.

Table 4.1: Design values for overall process architecture

Item	Basis or value	Interpretation
Feed	Liquid NH3	Pumped and vaporised
Cracking	2 x 5 MWth	Catalytic, 650 C target
Polishing	Guard bed plus PSA or membrane	Protect PEM stacks
Product	Hydrogen-rich gas	High purity to fuel cells
By-product	Nitrogen-rich stream	Controlled handling

4.2 Cracker mass balance

The theoretical stoichiometric relation requires 17 kg of ammonia for 3 kg of hydrogen. At the calculated voyage consumption of 1,704.3 t NH3, the theoretical hydrogen available before losses is 300.8 t. The design delivers 257.1 t to the fuel cells, corresponding to an overall yield of 85.5% relative to theoretical hydrogen in the consumed ammonia. This yield is represented as the product of a 90% effective cracking factor and a 95% purification and recovery factor. The factors are not vendor guarantees; they are a transparent design allowance. A rigorous model should distinguish equilibrium conversion, purge losses, start-up consumption and stack-quality hydrogen recovery rather than combining them into one number.

Table 4.2: Design values for cracker mass balance

Item	Basis or value	Interpretation
NH3 consumed	1,704.3 t	Voyage requirement
Theoretical H2	1,704.3 x 3/17	300.8 t
Cracking factor	90%	Effective conversion and availability
Purification factor	95%	Recovery to stack quality
Delivered H2	300.8 x 0.90 x 0.95	257.1 t

4.3 Cracker reaction and equilibrium

Ammonia cracking is endothermic and benefits from elevated temperature. The selected 650 C target is a compromise between conversion, catalyst durability, heat-transfer area and materials. Higher temperature can improve conversion but increases heat loss and thermal stress. Lower temperature reduces duty but risks ammonia slip and larger reactor volume. The equilibrium composition depends on pressure, temperature and inert dilution. Hydrogen removal downstream can increase apparent conversion, but the purifier itself consumes pressure drop and creates a purge. The process should therefore be solved as a coupled reactor-separator system, not as an isolated stoichiometric reactor.

Table 4.3: Design values for cracker reaction and equilibrium

Item	Basis or value	Interpretation
Reaction	2 NH3 -> N2 + 3 H2	Endothermic
Target temperature	650 C	Conceptual catalyst inlet
Pressure	20 bar	Feed and piping basis
Conversion allowance	90% effective	Includes availability
Model needed	Equilibrium plus kinetics	Vendor catalyst data

4.4 Cracker heat duty

A first heat-duty estimate is based on hydrogen production and an assumed effective duty of 3.5 MJ per kilogram of ammonia processed, including reaction enthalpy, sensible heating and heat losses. At a peak ammonia feed of roughly 110 t/day, the duty is approximately 4.46 MW. Two 5 MWth trains provide margin for warm-up and transient operation. The duty is intentionally separated from the fuel-cell electrical balance. If electric heaters supply the cracker, their demand reduces net propulsion power. If waste heat or a catalytic burner supplies part of the duty, the thermal integration becomes more efficient but adds controls and ammonia-slip risk. The final design should use a pinch analysis with realistic stack exhaust temperatures.

Table 4.4: Design values for cracker heat duty

Item	Basis or value	Interpretation
Specific effective duty	3.5 MJ/kg NH3	Conceptual allowance
Peak NH3 rate	110 t/day	Transient design basis
Thermal duty	110,000 x 3.5 / 86,400	4.46 MW
Installed trains	2 x 5 MWth	N plus 1 at reduced load
Next step	Pinch and dynamic duty model	Heat integration

4.5 Heat integration and waste heat

The fuel-cell exhaust and cracker outlet are the main heat sources. Recovered heat can vaporise ammonia, preheat cracker feed, maintain catalyst temperature during standby, and supply domestic hot water. The arrangement should avoid routing hot hydrogen-rich gas through accommodation or through equipment that cannot tolerate hydrogen embrittlement. A practical heat-recovery hierarchy is to satisfy safety-critical process preheating first, then recover medium-temperature heat for hotel services. Electricity production should not be credited twice: heat recovered from the fuel cells is useful energy but does not increase the net electrical output already used in the voyage calculation.

Table 4.5: Design values for heat integration and waste heat

Item	Basis or value	Interpretation
Priority 1	NH3 vaporisation	Avoid electric duty
Priority 2	Cracker feed preheat	Reduce reactor duty
Priority 3	Hotel hot water	Useful hotel service
Priority 4	Low-grade recovery	Only after safety review
Accounting rule	No double counting	Separate heat and power

4.6 Hydrogen purification

Hydrogen leaving the cracker contains nitrogen, residual ammonia, water vapour and unconverted species. PEM fuel cells are sensitive to ammonia and other contaminants, so a guard bed is placed before the final purifier. A PSA or membrane polishing stage then establishes the product purity and controls the purge composition. The 95% recovery factor in the voyage balance is an overall allowance for purification and purge. In a detailed design, purity and recovery would be solved together. Increasing recovery reduces purge losses but can allow contaminants to break through; increasing purity may require more stages and more compression power.

Table 4.6: Design values for hydrogen purification

Item	Basis or value	Interpretation
Inlet gas	H_2, N_2, NH_3, water	Cracker product
Water removal	Condenser and knockout	Protect adsorbent
NH_3 removal	Guard bed	Stack protection
Final stage	PSA or membrane	Purity and recovery
Design target	99.97 mol% H_2	NH_3 below 0.1 ppm

Chapter 5

Hydrogen power plant and propulsion

5.1 Fuel-cell technology selection

PEM fuel cells are selected for their fast response, modularity and suitability for variable marine load. The principal penalty is sensitivity to ammonia contamination and the need for high-purity hydrogen. Solid oxide fuel cells could improve electrical efficiency and tolerate some contaminants, but their high temperature and slow start-up complicate a cargo-ship duty cycle. Two 6 MW trains are preferable to one 12 MW train because they permit partial operation during maintenance and improve part-load efficiency. The final stack technology should be selected through a lifecycle comparison including catalyst replacement, membrane durability, cooling duty, salt exposure and marine vibration. The electrical architecture is treated as a marine microgrid rather than as a single generator replacement. Two PEM trains feed a common DC link through isolated converters, while battery buffering absorbs short transients associated with propeller pitch, thruster operation and compressor starts. The propulsion motor is supplied through redundant inverters, and essential auxiliaries are connected to an independent emergency bus. This arrangement keeps a local fault from becoming a total loss of propulsion. Fuel-cell sizing also requires an explicit degradation philosophy. The 12 MW gross installation is selected so that the stated 11 MW average electrical requirement can be met at beginning of life while retaining a 10 MW end-of-life target. The control system should dispatch the trains in a load-sharing window that avoids prolonged operation at very low current density, where efficiency and water management become less favourable.

Figure 5.1: Conceptual PEM fuel-cell machinery room with redundant trains, power electronics and thermal management.

Table 5.1: Design values for fuel-cell technology selection

Item	Basis or value	Interpretation
Technology	PEM	Fast response and modularity
Net efficiency	55% design basis	After auxiliaries
Train count	2 x 6 MW	Redundancy
Contaminant limit	NH3 below 0.1 ppm	Purification requirement
Selection gate	Vendor duty cycle data	Lifecycle comparison

5.2 Fuel-cell stack sizing

The electrical mission basis is 10 MW average shaft demand plus 1 MW average auxiliaries. The stack plant must therefore provide 11 MW net at beginning of life. A 12 MW gross installation, arranged as two 6 MW trains, leaves a practical margin for conversion losses and degradation. A small battery or supercapacitor handles rapid transients so that the cracker and stacks can ramp more slowly. At end of life, the design target is 10 MW net available from the stack plant, allowing the ship to reduce speed or shed non-essential loads while retaining safe manoeuvring. The installed capacity is therefore selected for a 10 MW shaft load plus auxiliaries.

Table 5.2: Design values for fuel-cell stack sizing

Item	Basis or value	Interpretation
Net shaft target	10 MW	Average shaft demand
Average auxiliaries	1 MW	Process and hotel loads
Gross stack capacity	12 MW recommended	Two 6 MW trains
Transient buffer	Battery or supercapacitor	Ramp control
End-of-life check	10 MW net minimum	Speed reduction if required

5.3 Voyage energy balance

The voyage time is calculated directly from distance and speed: 6,000 nmi divided by 14 kn equals 428.6 h. The shaft energy at 10 MW is 4,286 MWh and the average auxiliary energy at 1 MW is 429 MWh. The total delivered electrical energy is therefore 4,714 MWh. Dividing by 0.55 net fuel-cell efficiency gives 8,571 MWh of hydrogen chemical energy, or 30.86 TJ. At 120 MJ/kg, the hydrogen requirement is 257.1 t. This calculation is used in the present calculation report because it separates shaft power from chemical energy, states the efficiency boundary, and introduces a reserve after the calculation. The result is still sensitive to sea state, hull fouling, hotel load and the actual speed-power curve.

Table 5.3: Design values for voyage energy balance

Item	Basis or value	Interpretation
Voyage time	6,000 / 14	428.6 h
Shaft energy	10 x 428.6	4,286 MWh
Auxiliary energy	1 x 428.6	429 MWh
Chemical energy	4,714 / 0.55	8,571 MWh = 30.86 TJ
Hydrogen mass	30.86 TJ / 0.120	257.1 t

5.4 Speed-power relationship

The 10 MW shaft basis is a placeholder until resistance and propeller calculations are completed. For displacement vessels operating in a moderate Froude number range, required power rises steeply with speed. A small reduction from 14 kn can therefore extend range significantly, while a small increase can consume a disproportionate amount of hydrogen. A first sensitivity uses a cubic approximation, $P2/P1 = (V2/V1)^3$. At 12 kn, the idealised shaft requirement would be 6.30 MW relative to 10 MW at 14 kn. At 16 kn, it would be 14.94 MW. These values are screening estimates only; appendage drag, propeller efficiency and wave resistance must be added in a hull model.

Table 5.4: Design values for speed-power relationship

Item	Basis or value	Interpretation
Reference speed	14 kn	10 MW basis
Low speed	12 kn	6.30 MW cubic estimate
High speed	16 kn	14.94 MW cubic estimate
Sensitivity	P proportional to V^3	Screening only
Next model	Resistance plus propeller curve	Naval architecture

5.5 Propeller and shaftline concept

A single controllable-pitch propeller with a permanent-magnet motor is selected for the preliminary arrangement. Controllable pitch allows efficient manoeuvring without forcing the fuel cells to respond to every load change. The motor and inverter are sized for the maximum continuous shaft demand plus a short-term overload. The propeller diameter is constrained by draft and stern geometry. A larger diameter generally improves propulsive efficiency but increases tip-clearance and structural constraints. The final propeller must be checked for cavitation, vibration, ice or debris exposure, crash-stop performance and compatibility with the electric motor torque curve.

Table 5.5: Design values for propeller and shaftline concept

Item	Basis or value	Interpretation
Propulsion motor	Permanent-magnet electric	High efficiency and torque
Control	Variable speed and pitch	Manoeuvring flexibility
Power	10 MW continuous	Conceptual shaft target
Transmission	Direct or low-ratio gear	To be selected
Validation	Open-water and cavitation tests	Model basin

5.6 Electrical architecture

The electrical system is built around a medium-voltage DC bus supplied by two fuel-cell converters. DC distribution avoids unnecessary conversion stages and supports battery integration. Inverters feed the propulsion motor, while isolated converters supply hotel and control loads. Protection must account for bidirectional power flow, high fault currents and the slow response of the chemical plant. The battery is not sized to propel the ship for hours; it is sized for black start, load smoothing, emergency steering and safe shutdown. Selective coordination and arc-flash protection are mandatory detailed-design topics.

Table 5.6: Design values for electrical architecture

Item	Basis or value	Interpretation
Main bus	Medium-voltage DC	Fuel-cell and battery coupling
Propulsion	Dedicated inverter	Motor torque control
Hotel loads	Isolated converter	Accommodation and services
Battery role	Black start and transients	Not primary energy
Protection	Selective DC breakers	Fault isolation

Chapter 6

Safety, control and marine integration

6.1 Auxiliary power and hotel loads

The load basis treats 10 MW as the shaft requirement and adds auxiliaries explicitly. A more professional basis separates propulsion from hotel and process loads. Pumps, refrigeration, cracker heaters, compressors, ventilation, navigation and accommodation can consume approximately 0.8 to 1.2 MW depending on operating mode. The design therefore uses 10 MW shaft demand plus 1 MW average auxiliaries in the voyage balance. During harbour operation, shore power can carry hotel demand while the fuel-cell plant remains in standby. At sea, the plant controller limits non-essential loads if the cracker or one stack is unavailable. Hazardous-area design is organised around prevention, detection, isolation and recovery. Ammonia detection is provided at tank domes, transfer stations, compressor skids and low points; hydrogen detection is concentrated around the purifier, buffer vessels and fuel-cell room. Ventilation is arranged so that a detector can initiate local extraction before a concentration reaches the shutdown threshold. Relief discharge is routed to safe elevated locations with no direct path into accommodation or air intakes. The control philosophy is intentionally conservative. A loss of hydrogen purity trips the affected fuel-cell train and transfers the load to the healthy train or battery buffer. A loss of ammonia containment isolates the tank section, stops transfer pumps and starts the emergency ventilation mode. These actions are included in the conceptual design because they determine whether the ship can remain manoeuvrable after a single equipment failure.

Table 6.1: Design values for auxiliary power and hotel loads

Item	Basis or value	Interpretation
Process pumps	0.20 MW	NH3 and cooling circuits
Cracker electrical heat	0.40 to 1.0 MW	Depends on recovery
Ventilation and HVAC	0.15 MW	Hazardous spaces
Hotel and navigation	0.25 MW	Crew and bridge
Design auxiliary total	0.8 to 1.2 MW	Mode dependent

6.2 Cooling systems

PEM stacks reject a significant fraction of the hydrogen chemical energy as heat. At 55% net efficiency, an 11 MW electrical output corresponds to approximately 9.0 MW of rejected heat before considering additional losses. Not all of this heat is available at a useful temperature, so the cooling system must be split into high-temperature and low-temperature circuits. The ship uses seawater heat exchangers as the final sink, with closed fresh-water loops around the stacks and power electronics. Ammonia equipment is kept separate from seawater systems to prevent corrosion and contamination. The design must also consider reduced cooling capacity in warm seawater and fouling at the heat exchanger.

Table 6.2: Design values for cooling systems

Item	Basis or value	Interpretation
Stack heat rejection	11 / 0.55 - 11	9.0 MW theoretical
Primary coolant	Closed fresh water	Stack protection
Final sink	Seawater exchanger	Redundant pumps
Warm-water case	Reduced delta T	Capacity check
Recovery	Feed preheat and hotel water	Temperature dependent

6.3 Ventilation and hazardous spaces

Ammonia and hydrogen require different detection and ventilation strategies. Ammonia is toxic and heavier than air at some conditions; hydrogen is very light and has a wide flammability range. Spaces are therefore zoned, mechanically ventilated and equipped with gas detectors at both low and high points where appropriate. Ventilation is designed so that a leak does not drive gas toward accommodation, escape routes or ignition sources. Exhaust outlets are located away from air intakes. The control system initiates staged responses: alarm, increased ventilation, process isolation and emergency shutdown.

Table 6.3: Design values for ventilation and hazardous spaces

Item	Basis or value	Interpretation
Detection	NH3 and H2 sensors	Continuous monitoring
Ventilation	Dedicated extraction	No recirculation from hazardous spaces
Airflow	Negative pressure	Containment direction
Shutdown	Automatic isolation	On confirmed leak
Verification	Smoke and gas dispersion tests	Commissioning gate

6.4 Hazardous-area philosophy

The ammonia tanks, transfer station, cracker room, purifier room and hydrogen piping corridors are treated as hazardous areas for preliminary layout. Equipment selection must consider ignition sources, surface temperature, electrical classification and static discharge. The report does not assign a final zone classification because that depends on leak frequencies, ventilation rates and class rules. It does, however, reserve space for segregation, gas detection, emergency access, drainage and safe vent routing. The classification study is an early design gate, not a final paperwork exercise.

Table 6.4: Design values for hazardous-area philosophy

Item	Basis or value	Interpretation
Area	Primary hazard	Design response
Tank zone	Ammonia vapour	Closed piping and detection
Cracker room	Hydrogen and heat	Ventilation and isolation
Fuel-cell room	Hydrogen	Electrical classification
Vent mast	Controlled release	Safe discharge height
Gate	Formal HAZID and zoning	Class review

6.5 HAZID and major accident scenarios

The dominant scenarios are ammonia release during bunkering, tank overpressure, pipe rupture, cracker tube failure, hydrogen leak, fire in the machinery space, loss of cooling and collision damage to the tank zone. Each scenario requires a prevention layer, a detection layer and a consequence-mitigation layer. The design philosophy is to limit inventory in any one isolated section, maintain clear escape routes, and shut down automatically before a small leak becomes a large release. Relief and vent systems are designed to discharge to safe locations rather than into accommodation or enclosed machinery spaces.

Table 6.5: Design values for hazid and major accident scenarios

Item	Basis or value	Interpretation
Scenario	Prevention	Mitigation
Bunkering leak	Closed transfer and dry-break	Remote isolation and water curtain
Tank overpressure	Refrigeration and relief	Vent mast
Hydrogen leak	Double-wall piping	Detection and purge
Cooling loss	Redundant pumps	Load shed and shutdown
Collision	Protected midship tanks	Double hull and isolation

6.6 FMEA and redundancy

A qualitative failure mode and effects analysis supports the N plus 1 architecture. The loss of one cracker train should reduce available power but not remove steering or safe propulsion. The loss of one fuel-cell train should allow low-speed operation and a controlled diversion to port. Redundancy is not limited to duplicate equipment. It includes independent power feeds, separated cable routes, independent control logic, spare instrumentation, manual isolation capability and a maintenance plan. Common-cause failures such as shared cooling water, shared gas detection or a single DC bus must be treated explicitly.

Table 6.6: Design values for fmea and redundancy

Item	Basis or value	Interpretation
Failure	Immediate effect	Required response
One cracker offline	Reduced H2 production	Limit speed, retain one train
One stack offline	5 MW loss	Low-speed propulsion
Cooling pump failure	Thermal trip risk	Standby pump starts
DC bus fault	Power interruption	Segmented bus and battery
Control network fault	Loss of automation	Local safe shutdown

6.7 Control system and operating philosophy

The automation system coordinates ammonia feed, cracker temperature, purifier pressure, hydrogen quality, fuel-cell load and propulsion demand. The controller should not ask the chemical plant to follow rapid propeller transients. Instead, the battery and stack buffer follow electrical demand while the cracker ramps at a controlled rate. Control loops are separated into basic process control, safety instrumented functions and ship automation. A safety trip must remain effective if the supervisory computer or network fails. Manual local controls are provided for isolation, venting and emergency cooling.

Table 6.7: Design values for control system and operating philosophy

Item	Basis or value	Interpretation
Fast loop	Motor torque and battery	Milliseconds to seconds
Medium loop	Fuel-cell output	Seconds to minutes
Slow loop	Cracker temperature and feed	Minutes
Quality loop	NH3 slip and H2 purity	Continuous analyser
Safety layer	Isolation and purge	Independent logic

Chapter 7

Structural, operational and reliability design

7.1 Instrumentation and measurement uncertainty

The calculation quality depends on reliable measurement of ammonia mass, hydrogen flow, electrical output, stack temperature and gas purity. The report therefore treats uncertainty as part of the design rather than as an afterthought. Custody-transfer flowmeters and process analysers require calibration procedures and redundancy. A practical measurement uncertainty budget might allocate one percent to liquid ammonia mass, two percent to gas flow, one percent to electrical energy and a separate alarm limit for hydrogen purity. The fuel balance should be reconciled daily between tank inventory, process flow and shore bunkering records. Reliability is represented by functional redundancy rather than by duplicating every item. Two cracker trains, two fuel-cell trains, dual seawater cooling pumps and separated electrical switchboards are the principal availability measures. Common-cause failures remain possible, especially in cooling-water intake, control power and ventilation, so the verification plan must examine shared services explicitly. A numerical availability target is premature without vendor failure data, but the architecture identifies where that data will affect the design. The structural concept is likewise a design gate rather than a claim of approval. Tank supports must transmit sloshing, thermal contraction and collision loads into the hull without creating unacceptable local stress. The machinery foundations must tolerate rotating equipment and compressor vibration, while the hydrogen lines require flexibility analysis at cryogenic and hot operating boundaries. The report therefore records loads and interfaces that a later class calculation must close.

Table 7.1: Design values for instrumentation and measurement uncertainty

Item	Basis or value	Interpretation
Measurement	Target uncertainty	Use
NH3 mass	About 1%	Voyage fuel balance
H2 flow	About 2%	Purifier performance
Electrical energy	About 1%	Efficiency reporting
NH3 analyser	Alarm before slip limit	Stack protection
Data historian	One-second critical tags	Root-cause analysis

7.2 Emissions and environmental performance

The ship has no carbon in the ideal ammonia-to-hydrogen reaction, but it is not automatically impact-free. Electricity used for ammonia synthesis, hydrogen leakage, nitrogen oxide formation during any burner operation, refrigerant leakage and upstream ammonia transport all affect lifecycle performance. At the point of use, the fuel-cell exhaust is mainly water and nitrogen. The small trim burner can produce NOx if ammonia slips through or if combustion is poorly mixed, so start-up and emergency operation require separate emissions controls. The report therefore distinguishes zero carbon at the stack from lifecycle carbon intensity.

Table 7.2: Design values for emissions and environmental performance

Item	Basis or value	Interpretation
Point-of-use CO2	Near zero for H2 electrochemical use	No carbon in feed
NH3 slip	Controlled by guard bed	Continuous monitoring
NOx	Relevant to burner mode	Low-slip combustion
Refrigerant	Closed system	Leak detection
Lifecycle metric	kg CO2e per voyage	Supply-chain study

7.3 Structural concept and load cases

The tank supports, cofferdams and pipe anchors introduce concentrated loads into the hull. The design must account for full and partial tanks, sloshing, thermal contraction, collision loads, longitudinal bending, vibration and emergency manoeuvres. Tank supports cannot be sized from static weight alone. The first structural model should include the tank saddles, deck openings, machinery foundations and double-hull protection. Finite-element analysis then checks local stress and fatigue around nozzles and supports. This report provides arrangement intent but does not claim scantlings.

Table 7.3: Design values for structural concept and load cases

Item	Basis or value	Interpretation
Static case	Full tank and full cargo	Global strength
Partial fill	Sloshing and free surface	Tank support loads
Thermal case	-33 C tank contraction	Pipe flexibility
Collision case	Side impact protection	Double hull
Fatigue case	Pressure and vibration cycles	FEA and class review

7.4 Stability and free-surface effect

Refrigerated ammonia tanks create a significant free-surface risk when partially filled. Two equal tanks reduce the severity of a single tank level change, but the loading manual must still evaluate every transfer stage. Ballast and cargo distribution must keep metacentric height, trim and propeller immersion within acceptable limits. A preliminary stability workflow begins with lightship, cargo, ammonia, ballast and consumable conditions. It then evaluates intact stability, damage cases, free-surface correction and wind heeling. The present design basis reserves tank geometry but does not substitute for a certified stability booklet.

Table 7.4: Design values for stability and free-surface effect

Item	Basis or value	Interpretation
Main risk	Free surface in partially filled tanks	Loading manual
Trim control	Ballast and tank sequencing	Propeller immersion
Damage case	Side tank breach	Flooding model
Wind case	Large lateral area	Heeling arm
Approval gate	Intact and damage stability	Class submission

7.5 Seakeeping and operability

The chemical equipment must remain within acceleration, roll and vibration limits. Cracker catalysts, membrane modules, pumps and fuel-cell stacks cannot be treated as ordinary cargo. The machinery foundation and pipe flexibility design must accommodate ship motion without inducing leaks or catalyst damage. The selected mission assumes the vessel can reduce speed in heavy weather. This operational flexibility is part of the fuel calculation: a weather margin is included in the ammonia inventory rather than hidden inside an optimistic average speed. A seakeeping model should define allowable pitch, roll, acceleration and sloshing limits.

Table 7.5: Design values for seakeeping and operability

Item	Basis or value	Interpretation
Motion	Roll, pitch and vertical acceleration	Equipment qualification
Weather mode	Speed reduction	Fuel reserve protection
Foundation	Shock and vibration isolation	Machinery integrity
Pipework	Flexible supports	Thermal and motion loads
Validation	Seakeeping and fatigue model	Model tests or CFD

7.6 Reliability, availability and maintainability

A shipboard energy system must be repairable at sea. The modular arrangement provides access for replacing cracker catalyst cartridges, purifier beds, pumps, valves and fuel-cell modules. Maintenance intervals should be aligned with port calls rather than assumed to be unlimited. Availability is governed by common-cause failures as much as by individual component reliability. Spare parts, bypasses, flushing connections and isolation boundaries are therefore part of the design. A reliability block diagram should quantify the probability of retaining minimum manoeuvring power during a voyage.

Table 7.6: Design values for reliability, availability and maintainability

Item	Basis or value	Interpretation
Maintainable item	Planned action	Design provision
Catalyst	Replace cartridge	Removable reactor modules
Purifier bed	Regenerate or replace	Parallel beds and bypass
Fuel-cell stack	Module change-out	Two independent trains
Pump	Seal and bearing service	Standby pump
Analyser	Calibration	Sample conditioning and spare

7.7 Operations and crew competence

The ship requires competency in ammonia handling, hydrogen safety, high-voltage DC systems and fuel-cell operation. The crew workflow must be designed before the final equipment layout because access, sampling, isolation and emergency response depend on human actions. Training should use normal, abnormal and emergency scenarios. A simulator can rehearse bunkering, leak detection, cracker trip, loss of cooling, fuel-cell degradation and controlled return to port. The operating manual must define who has authority to initiate an emergency shutdown and how the ship is restarted safely.

Table 7.7: Design values for operations and crew competence

Item	Basis or value	Interpretation
Competence	Ammonia and hydrogen handling	Initial and recurrent training
Electrical	Medium-voltage DC and battery	Authorisation and isolation
Emergency	Leak, fire and loss of propulsion	Drills and simulator
Sampling	Gas purity and NH3 slip	Laboratory procedure
Documentation	Muster, permit and lockout	Controlled manuals

Chapter 8

Economics, sensitivity and verification

8.1 Maintenance strategy

Maintenance is organised around condition monitoring and port windows. The most important indicators are catalyst conversion, ammonia slip, stack voltage spread, cooling approach temperature, tank boil-off, pump vibration and purifier pressure drop. The vessel should carry critical spares for valves, analysers, pump seals, power-electronics modules and purifier beds. Catalyst and fuel-cell replacement are larger interventions and must be scheduled with a shore facility. The report recommends a maintenance reserve in the economic model. The economic result should be read as a range-based screening estimate. Equipment cost, installation cost, class work, commissioning and downtime can easily move the total by tens of percent at this maturity. The value of the calculation is comparative: it shows how much of the penalty comes from ammonia inventory, the cracker and purification plant, the fuel-cell system and the additional safety infrastructure. A future estimate should replace every allowance with vendor quotations and an integrated shipyard weight report. Sensitivity is therefore reported against the parameters that dominate the result. Fuel-cell efficiency changes both hydrogen mass and ammonia inventory; speed changes voyage time with an approximately inverse relationship; and usable tank fraction changes the reserve without changing the chemical duty. Presenting these sensitivities prevents a single rounded design point from being mistaken for a prediction.

Table 8.1: Design values for maintenance strategy

Item	Basis or value	Interpretation
Condition tag	Trigger	Action
NH3 slip	Rising trend	Inspect guard bed
Stack voltage spread	Increasing spread	Balance or replace module
Cooling approach	Temperature rise	Clean exchanger
Pump vibration	Alarm threshold	Switch standby and inspect
Boil-off	Above model	Check insulation and refrigeration

8.2 CAPEX structure

A conceptual cost estimate should be organised by equipment package rather than by a single cost per tonne. The principal packages are hull and conventional marine systems, ammonia tanks, cargo handling, crackers, purification, fuel-cell stacks, power electronics, batteries, safety systems and integration engineering. Because vendor prices are uncertain, the report recommends a range-based estimate with explicit contingency. The fuel-cell and cracker packages are likely to dominate the incremental cost over a conventional ship, while the hull and cargo systems dominate total installed capital.

Table 8.2: Design values for capex structure

Item	Basis or value	Interpretation
Package	Cost driver	Estimate maturity
NH3 tanks	Refrigerated containment	Conceptual
Crackers	Catalyst and heat transfer	Conceptual
Purification	Membrane or PSA package	Vendor enquiry
Fuel cells	Stack power and replacement	Vendor enquiry
Integration	Hazardous marine installation	Shipyard estimate

8.3 OPEX structure

Operating expenditure includes ammonia fuel, electricity in harbour, catalyst replacement, purifier media, fuel-cell stack degradation, refrigeration, crew training, inspections and maintenance. The ammonia cost must be reported separately from the conversion efficiency so that fuel price sensitivity can be understood. A simple voyage OPEX model multiplies 1,704 t of ammonia by the delivered ammonia price, then adds fixed ship costs and an annualised replacement reserve. The report does not claim a market price because the supply contract, terminal, origin and certification route are unknown.

Table 8.3: Design values for opex structure

Item	Basis or value	Interpretation
Variable cost	Ammonia consumed	1,704 t per design voyage
Process cost	Electricity and cooling	Mode dependent
Replacement reserve	Catalyst and stacks	Annualised
Fixed cost	Crew, insurance, class	Ship specific
Sensitivity	Ammonia price and efficiency	Primary uncertainty

8.4 Sensitivity to fuel-cell efficiency

Fuel-cell efficiency has a direct influence on hydrogen and ammonia demand. For the same 11 MW total electrical voyage load, at 50% net efficiency the hydrogen requirement rises to 282.9 t. At 60%, it falls to 235.7 t. The corresponding ammonia requirement changes approximately in proportion, before adding the same reserve policy. This sensitivity demonstrates why stack degradation and cooling performance matter economically. A design that begins at 55% but falls to 50% at end of life can consume roughly 10% more ammonia for the same voyage. The installed inventory should be checked against the end-of-life case, not only the new-build case.

Table 8.4: Design values for sensitivity to fuel-cell efficiency

Item	Basis or value	Interpretation
Efficiency	H2 requirement	NH3 before reserve
50%	282.9 t	1,875 t
55%	257.1 t	1,704 t
60%	235.7 t	1,562 t
Design choice	55% net basis	End-of-life check required

8.5 Sensitivity to speed and route

The cubic speed approximation shows that speed is a powerful operational lever. A 12 kn passage takes 500 h but lowers idealised shaft power to 6.30 MW. A 16 kn passage takes 375 h but increases idealised shaft power to approximately 14.94 MW. The total energy is therefore not constant with speed. The correct speed policy depends on charter revenue, weather, berth windows and ammonia price. The ship automation should expose a speed-energy curve to the operator rather than hiding it in a single design point. A voyage optimiser can then trade schedule against fuel reserve.

Table 8.5: Design values for sensitivity to speed and route

Item	Basis or value	Interpretation
Speed	Time for 6,000 nmi	Cubic power screen
12 kn	500 h	6.30 MW
14 kn	428.6 h	10.00 MW
16 kn	375 h	14.94 MW
Decision	Charter versus energy	Optimise per voyage

8.6 Comparison with alternative propulsion

The ammonia-to-hydrogen route avoids carrying compressed hydrogen but adds a cracker, purifier, thermal system and contaminant-control problem. Direct ammonia combustion avoids onboard cracking but introduces NOx and combustion-control challenges. Battery propulsion has high round-trip efficiency but insufficient energy density for the selected ocean mission without major changes to route and vessel size. The appropriate comparison is therefore system-level: tank volume, bunkering network, power conversion, maintenance, emissions, safety and end-of-life. No single technology dominates every route. The proposed design is most credible where ammonia bunkering is available and long range is more important than maximum conversion efficiency.

Table 8.6: Design values for comparison with alternative propulsion

Item	Basis or value	Interpretation
Option	Strength	Main penalty
NH3 to H2 PEM	Low point-of-use carbon, modular	Cracker and purity burden
Direct NH3 engine	Simpler fuel conversion	NOx and combustion control
Battery	High efficiency	Very high mass and volume
Methanol route	Liquid handling maturity	Carbon-containing fuel
Selection basis	Route and infrastructure	Owner decision

8.7 Design verification plan

The next stage should be a formal verification plan. Process verification includes Aspen or gPROMS mass and energy balances, equilibrium and kinetic cracker models, purifier cycle simulation and heat integration. Marine verification includes hull resistance, propeller performance, stability, structural FEA, hazardous-area layout, ventilation CFD and class review. Each calculation should have an owner, an input data source, a validation method and an acceptance criterion. This prevents a polished report from being mistaken for a validated production design. The academic value of the present report is that it makes those future checks explicit.

Table 8.7: Design values for design verification plan

Item	Basis or value	Interpretation
Discipline	Model	Acceptance evidence
Process	Dynamic cracker and purifier	Vendor or pilot data
Naval	Resistance and propeller	Model basin or CFD
Structural	Tank and hull FEA	Class review
Safety	HAZID, HAZOP and CFD	Approved safeguards
Economics	Vendor quotations	Range-based estimate

Chapter 9

Conclusions

9.1 Conclusions

The proposed cargo ship is technically coherent at conceptual level: ammonia is stored as a dense liquid, converted onboard in two redundant cracker trains, purified to fuel-cell quality, and converted to electric propulsion through two PEM trains. The 6,000 nmi mission requires approximately 1,704 t of ammonia on the stated 11 MW total electrical basis, while 2,500 t of usable inventory provides reserve for degradation and operations. The most important principal design choices are the separation of shaft energy from chemical energy, explicit auxiliary loads, corrected hydrogen yield, reserve accounting, tank volume estimation, speed sensitivity and a verification plan. The design is ready for a detailed academic model or a pre-FEED study, but not for procurement without the validation steps listed above.

Table 9.1: Design values for conclusions

Item	Basis or value	Interpretation
Headline result	10 MW shaft + 1 MW auxiliaries	Two 6 MW PEM trains
Voyage basis	6,000 nmi at 14 kn	428.6 h
NH3 consumption	1,704 t	Before selected inventory reserve
Installed inventory	2,500 t	Two refrigerated tanks
Design status	Conceptual pre-FEED	Validation required

Appendix A

Extended engineering calculations

This appendix makes the principal design closures explicit. Values are rounded only after the balance has been evaluated, and every result is tied to the declared 6,000 nmi, 14 kn mission. The calculations establish order of magnitude, identify controlling variables and define inputs for detailed design.

A.1 Mission time, propulsion energy and chemical energy

The voyage time follows directly from the nautical definition of a knot:

$$t_v = \frac{D}{V} = \frac{6000\ \text{nmi}}{14\ \text{nmi}\,\text{h}^{-1}} = 428.571\ \text{h} = 17.857\ \text{d}. \tag{A.1}$$

The electrical load is separated into shaft and hotel demand. For an average shaft requirement of 10 MW and auxiliary demand of 1 MW:

$$P_{el} = P_{shaft} + P_{aux} = 10 + 1 = 11\ \text{MW}, \qquad E_{el} = P_{el} t_v = 4714.286\ \text{MWh}. \tag{A.2}$$

The corresponding delivered electrical energy is 16.971 TJ. With a net fuel-cell efficiency of 0.55 and hydrogen lower heating value of 120 MJ kg^{-1}:

$$E_{H2} = \frac{16.971}{0.55} = 30.856\ \text{TJ}, \qquad m_{H2} = \frac{30.856 \times 10^6}{120} = 257.14\ \text{t}. \tag{A.3}$$

A.2 Ammonia reaction and complete mass balance

The stoichiometric reaction is $2\,NH_3 \rightarrow N_2 + 3\,H_2$. The ideal hydrogen mass fraction is:

$$w_{H2,stoich} = \frac{3M_{H2}}{2M_{NH3}} = \frac{3 \times 2.016}{2 \times 17.031} = 0.1776. \tag{A.4}$$

Applying 90% cracker conversion and 95% hydrogen recovery gives an effective yield of $0.1776 \times 0.90 \times 0.95 = 0.1519$. The conservative report ratio $y = 0.150882$ therefore gives:

$$m_{NH3,cons} = \frac{257.14}{0.150882} = 1704.26 \text{ t}. \tag{A.5}$$

The associated nitrogen production is estimated from the stoichiometric ratio 28/6:

$$m_{N2} = m_{H2}\frac{28}{6} = 1199.99 \text{ t}. \tag{A.6}$$

This is a process-stream result, not a stored cargo requirement; the purge and separation system must be sized for this nitrogen-rich flow.

A.3 Hourly and daily process rates

The average hydrogen production rate over the passage is:

$$\dot{m}_{H2} = \frac{257.14}{428.571} = 0.600 \text{ t h}^{-1} = 14.40 \text{ t d}^{-1}. \tag{A.7}$$

The corresponding ammonia consumption is:

$$\dot{m}_{NH3} = \frac{1704.26}{428.571} = 3.977 \text{ t h}^{-1} = 95.45 \text{ t d}^{-1}. \tag{A.8}$$

For two trains, the nominal duty is 47.7 t d^{-1} of ammonia per train. A 15% turndown margin gives a design feed rate of 54.9 t d^{-1} per train when both trains are online.

A.4 Tank volume, geometry and reserve accounting

The usable ammonia inventory is 2,500 t. With a liquid density of 850 kg m^{-3}:

$$V_{liq} = \frac{2500 \times 10^3}{850} = 2941.18 \text{ m}^3. \tag{A.9}$$

For two tanks, an 80% fill limit and 90% geometric utilisation, the gross volume per tank is:

$$V_{tank,gross} = \frac{2941.18}{2 \times 0.80 \times 0.90} = 2042.49 \text{ m}^3. \tag{A.10}$$

The inventory reserve is:

$$m_{reserve} = 2500 - 1704.26 = 795.74 \text{ t}, \qquad f_{reserve} = 31.83\%. \tag{A.11}$$

At the nominal consumption rate this reserve corresponds to 200.1 h, or 8.34 days, of additional operation.

A.5 Cracker duty, heat recovery and cooling load

The assumed specific cracker duty is 3.5 MJ kg^{-1} NH_3. At 95.45 t d^{-1}:

$$Q_{cracker} = \frac{95.45 \times 10^3 \times 3.5}{86400} = 3.87 \text{ MW}. \tag{A.12}$$

Using the conservative 110 t d^{-1} design rate gives 4.46 MW. Fuel-cell reject heat is:

$$Q_{FC,rej} = P_{el}\left(\frac{1}{\eta_{FC}} - 1\right) = 11\left(\frac{1}{0.55} - 1\right) = 9.0 \text{ MW}. \tag{A.13}$$

If 35% is recoverable at the required temperature level, useful recovered duty is 3.15 MW and the trim heater duty is $Q_{trim} = 4.46 - 3.15 = 1.31$ MW.

A.6 Hydrogen purification and compression power

The hydrogen mass flow at nominal load is 0.1667 kg s^{-1}. A 20 bar to 30 bar compression step is estimated with:

$$W_{iso} = \dot{n}RT \ln\left(\frac{p_2}{p_1}\right). \tag{A.14}$$

For 323 K and 70% overall efficiency, the installed compressor power is selected as 0.29 MW per train including margin.

A.7 Cooling-water requirement

The non-recovered fuel-cell heat is estimated at 5.85 MW. With a 10 K cooling-water rise and $c_p = 4.18$ kJ kg^{-1} K^{-1}:

$$\dot{m}_w = \frac{5.85 \times 10^3}{4.18 \times 10} = 140 \text{ kg s}^{-1}. \tag{A.15}$$

Two 70 kg s^{-1} pumps provide the average duty, with a third installed pump as standby. At 25 m head and 75% efficiency, hydraulic power per duty pump is 22.9 kW.

A.8 Electrical distribution and battery buffer

Two 6 MW PEM trains provide 12 MW gross installed capacity. For a 15 s transient at 3 MW above steady load:

$$E_{bat} = P\Delta t = 3 \times 15 = 45 \text{ MJ} = 12.5 \text{ kWh}. \tag{A.16}$$

Applying an 80% usable state-of-charge window and 90% converter efficiency yields a minimum of 17.4 kWh. A 1 MWh battery is therefore not required by energy capacity alone; it is selected only if black-start, peak-shaving or spinning-reserve capability is required.

A.9 Propulsive power cross-check

For a first-order speed sensitivity, constant displacement and similar hull form give $P \propto V^3$. Relative to 14 kn:

$$P(V) = 10 \left(\frac{V}{14}\right)^3 \text{ MW.} \tag{A.17}$$

At 12 kn the shaft demand is 6.30 MW and at 16 kn it is 14.95 MW; voyage times are 500 h and 375 h respectively. Speed uncertainty must therefore be carried through the chemical inventory.

A.10 Uncertainty propagation

For independent fractional uncertainties in efficiency, voyage time and process yield:

$$\left(\frac{\sigma_m}{m}\right)^2 = \left(\frac{\sigma_t}{t}\right)^2 + \left(\frac{\sigma_\eta}{\eta}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2. \tag{A.18}$$

Using 5%, 4% and 5% gives $\sigma_m/m = 8.12\%$, or approximately ±138 t on the ammonia requirement before owner reserve.

A.11 Efficiency and speed sensitivity table

Table A.1: Independent sensitivity calculations around the design point

Case	Speed (kn)	η_{FC}	m_{H2} (t)	m_{NH3} (t)
Base	14	55%	257.14	1704.26
Slow passage	12	55%	300.00	1988.37
Fast passage	16	55%	225.00	1491.28
Low efficiency	14	50%	282.86	1874.69
High efficiency	14	60%	235.71	1562.24

Appendix B

Calculation worksheets

B.1 Voyage energy closure

The independent calculation is:

$$t = \frac{D}{V} = \frac{6000}{14} = 428.571 \text{ h.} \tag{B.1}$$

$$E_{el} = (P_{shaft} + P_{aux})t = (10 + 1) \times 428.571 = 4714.286 \text{ MWh.} \tag{B.2}$$

$$m_{H2} = \frac{E_{el} \times 3.6}{\eta_{FC} LHV_{H2}} = \frac{4714.286 \times 3.6}{0.55 \times 120} = 257.14 \text{ t.} \tag{B.3}$$

B.2 Ammonia-to-hydrogen closure

$$y_{NH3 \to H2} = 0.90 \times 0.95 \times \frac{3}{17} = 0.150882. \tag{B.4}$$

$$m_{NH3} = \frac{257.14}{0.150882} = 1704.26 \text{ t.} \tag{B.5}$$

B.3 Tank volume and reserve

$$V_{liq} = \frac{2500}{0.850} = 2941.18 \text{ m}^3, \qquad V_{gross} = \frac{2941.18}{0.80 \times 0.90} = 4084.97 \text{ m}^3. \tag{B.6}$$

B.4 Thermal and sensitivity checks

$$Q_{cracker} = \frac{110000 \times 3.5}{86400} = 4.456 \text{ MW.} \tag{B.7}$$

$$Q_{FC,rej} = \frac{11}{0.55} - 11 = 9.0 \text{ MW.} \tag{B.8}$$

Table B.1: Efficiency sensitivity

η_{FC}	m_{H2} (t)	m_{NH3} (t)	Reserve (t)
50%	282.86	1874.69	625.31
55%	257.14	1704.26	795.74
60%	235.71	1562.24	937.76

Appendix C

References and source archive

The bibliography lists the technical papers, source PDFs, maritime data, cost references and equipment sources used for the ammonia, hydrogen, fuel-cell and ship-design basis. Web pages and vendor data should be rechecked at FEED.

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Project source files

- `final assignment.pdf` (Fausto Gallucci; assignment brief).
- `hydrogen production from ammonia reactor.pdf` (Devkota et al., 2023).
- `hydrogen separation.pdf` (Trangwachirachai et al., 2024).
- `Fuel cell parameters.pdf` (Ahluwalia et al., 2004).
- `Transportation and Storage of Ammonia.pdf`.

The design requires vendor, shipyard, structural and class validation before procurement.