

# Closed-Cycle Ammonia OTEC: Thermodynamic Basis and Net Power Yield

A first-principles treatment of the Carnot ceiling, the practical Rankine cycle on anhydrous ammonia, and the parasitic-load accounting that sets net electrical output for utility-scale Ocean Thermal Energy Conversion in the TROIB Gulf zone.

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## CONCEPTUAL ENGINEERING BRIEF

Figures, performance estimates, and projections are illustrative and forward-looking; they describe a proposed system architecture and do not represent built, measured, or independently verified results.

## ABSTRACT

Ocean Thermal Energy Conversion (OTEC) extracts work from the standing temperature difference between warm tropical surface water ( $\approx 24\text{--}25\text{ }^\circ\text{C}$ ) and cold abyssal water ( $\approx 4\text{ }^\circ\text{C}$ ) drawn from roughly 915 m (3,000 ft) depth. With a gradient of only  $\Delta T \approx 20\text{ }^\circ\text{C}$  the ideal Carnot ceiling is near 7 %, and a real closed-cycle plant converts on the order of 3–4 % of gross thermal throughput to *net* electricity after parasitic loads. This brief develops the thermodynamic basis of a closed Rankine cycle using anhydrous ammonia ( $\text{NH}_3$ ) as the working fluid, maps each stage to the TROIB plant schematic, and presents an energy balance that resolves gross versus net power across the proposed Gulf of Mexico deployment ramp (50  $\text{MW}_{\text{gross}}$  / 35  $\text{MW}_{\text{net}}$  at Year 3 rising to 500  $\text{MW}_{\text{gross}}$  / 350  $\text{MW}_{\text{net}}$  across a ten-platform cluster by Year 10). The dominant parasitic load — cold-water pumping —

is shown to be the central design driver, dictating both heat-exchanger surface area and cold-water-pipe diameter.

## 1 The Resource and the Carnot Ceiling

The tropical and subtropical ocean is a continuously recharged thermal reservoir. Solar flux maintains a warm mixed layer while the deep ocean retains cold, dense water that originated at the poles. In the TROIB Gulf of Mexico zone the design state points are a warm surface reservoir at  $T_{\text{warm}} \approx 24\text{--}25\text{ }^\circ\text{C}$  and a cold reservoir at  $T_{\text{cold}} \approx 4\text{ }^\circ\text{C}$  accessed through a 915 m cold-water pipe (CWP). Because OTEC is a heat engine, its *maximum theoretically attainable* efficiency is the Carnot efficiency evaluated on **absolute** temperatures:

$$\eta_{\text{Carnot}} = (T_{\text{warm}} - T_{\text{cold}}) / T_{\text{warm}} \quad (1)$$

Substituting  $T_{\text{warm}} \approx 298\text{ K}$  (25 °C) and  $T_{\text{cold}} \approx 277\text{ K}$  (4 °C):

$$\eta_{\text{Carnot}} = (298 - 277) / 298 = 21 / 298 \approx 0.070 \approx \mathbf{7.0\%} \quad (2)$$

This 7 % ceiling is the single most important fact in OTEC engineering. Unlike a combustion plant burning fuel near 1,800 K, an OTEC plant works across a vanishingly small temperature ratio, so the **absolute** conversion efficiency is low *by physics, not by engineering deficiency*. The design response is not to chase efficiency but to move enormous volumes of water cheaply: the resource is free and effectively unlimited, so economics are governed by the capital cost of heat-transfer area and pumping, not by fuel.

## 2 The Closed Rankine Cycle on Ammonia

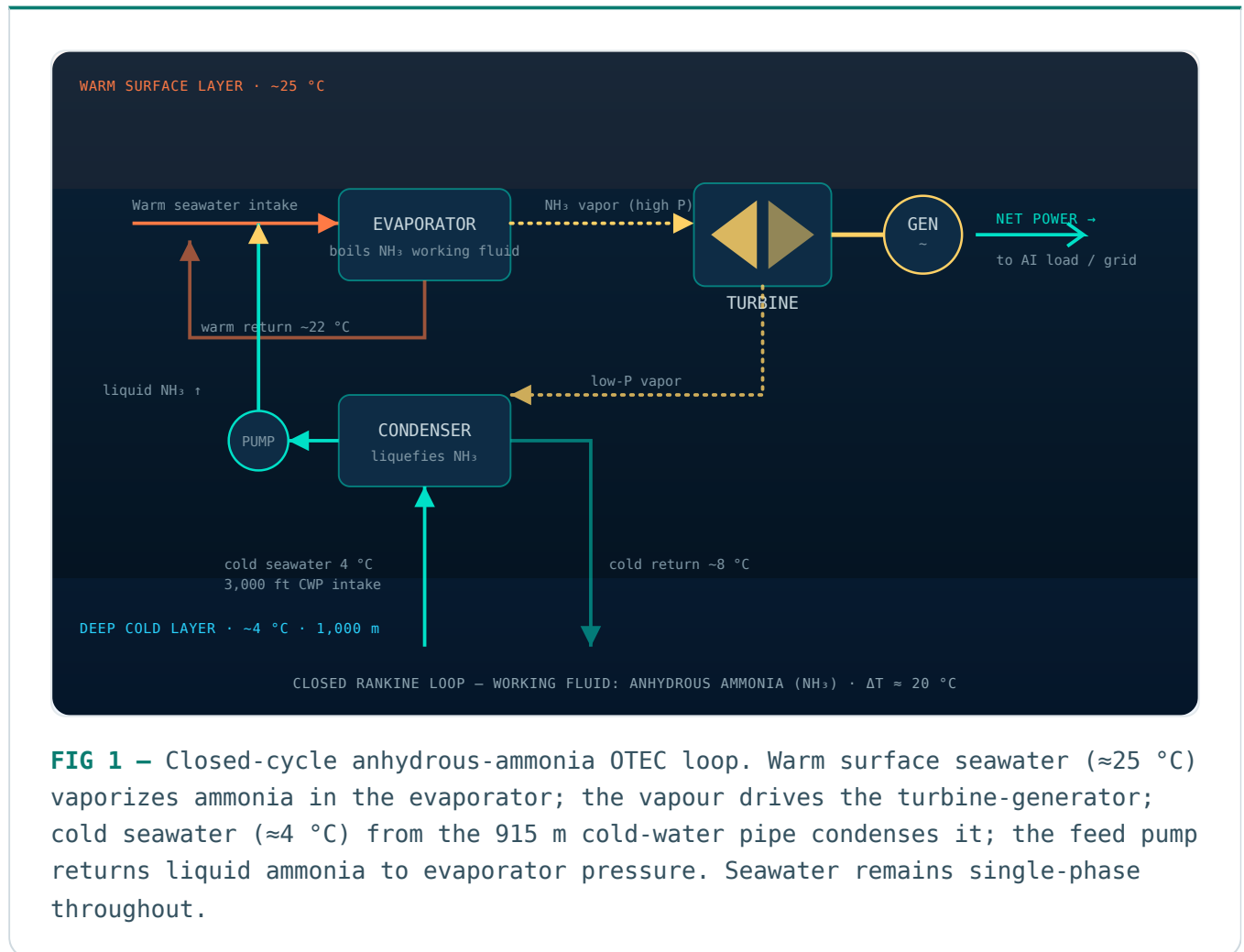
TROIB adopts a **closed-cycle** architecture. A low-boiling-point working fluid is circulated in a sealed loop; seawater never changes phase and never contacts the turbine. Anhydrous ammonia (NH<sub>3</sub>) is selected because it boils near  $-33\text{ }^\circ\text{C}$  at atmospheric pressure, has an exceptionally high latent heat of vaporization ( $\approx 1,370\text{ kJ/kg}$ ), and exhibits favourable heat-

transfer coefficients — allowing a compact pressure-driven cycle within the narrow 20 °C window.

## 2.1 Cycle stages

The four canonical stages, mapped to the schematic in Figure 1, are:

**1. Evaporator.** Warm surface seawater ( $\approx 25$  °C) flows through a plate or shell-and-tube exchanger and boils pressurized liquid ammonia into saturated vapour at roughly 9–10 bar. **2. Turbine.** The high-pressure vapour expands across a turbine-generator, producing shaft work. **3. Condenser.** Cold deep seawater ( $\approx 4$  °C) condenses the low-pressure exhaust vapour back to liquid at roughly 5–6 bar. **4. Feed pump.** A small feed pump returns the condensate to evaporator pressure, closing the loop. The net cycle work is the turbine output less the feed-pump work; the dominant external parasitic is the *seawater* pumping that feeds both heat exchangers.



### 3 Turbine Work and the Energy Balance

The gross shaft power produced by the turbine is the working-fluid mass flow multiplied by the enthalpy drop across the expansion:

$$\dot{W}_{\text{turbine}} = \dot{m}_{\text{NH}_3} \cdot \Delta h = \dot{m}_{\text{NH}_3} \cdot (h_{\text{in}} - h_{\text{out}}) \quad (3)$$

where  $\dot{m}_{\text{NH}_3}$  is the ammonia mass-flow rate (kg/s) and  $\Delta h$  is the isentropic enthalpy drop (kJ/kg) modified by turbine isentropic efficiency. Because  $\Delta h$  across the small available pressure ratio is modest, large electrical output demands large working-fluid mass flow — which in turn demands large heat-exchanger throughput on both the warm and cold seawater sides.

Net electrical output is gross generator output minus the sum of parasitic loads:

$$P_{\text{net}} = P_{\text{gross}} - P_{\text{parasitic}} = P_{\text{gross}} - (P_{\text{cwp}} + P_{\text{wwp}} + P_{\text{feed}} + P_{\text{aux}}) \quad (4)$$

where  $P_{\text{cwp}}$  is cold-water-pipe pumping,  $P_{\text{wwp}}$  warm-water pumping,  $P_{\text{feed}}$  the ammonia feed pump, and  $P_{\text{aux}}$  auxiliaries. Empirically, parasitic loads consume on the order of 25–35 % of gross output in a well-designed plant, collapsing the  $\approx 7$  % Carnot ceiling to a delivered **net** efficiency near 3–4 %. Table 1 gives an illustrative single-platform energy balance.

**TABLE 1** – Illustrative single-platform OTEC energy balance (Year-3 reference module).

Stream / term	Symbol	Value	Note
Gross generator output	$P_{gross}$	50.0 MW	turbine-generator terminal
Cold-water pumping	$P_{cwp}$	-9.5 MW	dominant parasitic
Warm-water pumping	$P_{wwp}$	-3.5 MW	shorter lift
Ammonia feed pump	$P_{feed}$	-1.2 MW	closed loop
Auxiliaries / controls	$P_{aux}$	-0.8 MW	instrumentation, BOP
<b>Net export power</b>	$P_{net}$	≈ 35.0 MW	30 % parasitic fraction

## 4 Heat-Exchanger Sizing Intuition

Heat transfer obeys  $Q = U \cdot A \cdot \Delta T_{lm}$ , where  $U$  is the overall heat-transfer coefficient,  $A$  the surface area, and  $\Delta T_{lm}$  the log-mean temperature difference. In a conventional power plant  $\Delta T_{lm}$  may be hundreds of degrees; in OTEC the *available* gradient is 20 °C, and after allocating temperature pinch to the evaporator and condenser the working  $\Delta T_{lm}$  per exchanger is only a few degrees. Since  $A$  scales inversely with  $\Delta T_{lm}$ , OTEC heat exchangers are physically enormous — they are the dominant capital item and the principal reason OTEC has historically remained at demonstration scale.

TROIB mitigates this two ways: (i) high-performance plate or roll-bonded aluminium exchangers that raise  $U$ , and (ii) co-locating the power block on a re-used deepwater platform (see companion brief TROIB-EB-02), which amortizes the structural cost of supporting heavy exchangers over an existing asset.

**7.0 %**

CARNOT CEILING ·  
 $\Delta T$  20 °C

**3–4 %**

NET DELIVERED  
EFFICIENCY

**~30 %**

PARASITIC  
FRACTION OF  
GROSS

**915 m**

COLD-WATER-PIPE  
DEPTH

## 5 Cold-Water Pipe Flow and the Dominant Parasitic

The cold-water pump is the single largest parasitic load because it must lift and accelerate a very large volumetric flow through a long, large-diameter pipe. The pumping power required is:

$$P_{\text{cwp}} = (\rho \cdot g \cdot Q \cdot H_{\text{loss}}) / \eta_{\text{pump}} \quad (5)$$

where  $Q$  is volumetric flow ( $\text{m}^3/\text{s}$ ),  $\rho$  seawater density ( $\approx 1,025 \text{ kg/m}^3$ ),  $g$  gravitational acceleration,  $H_{\text{loss}}$  the total dynamic head (friction plus the small density-difference penalty between the warm column and the colder, denser pumped water), and  $\eta_{\text{pump}}$  pump efficiency. Note that OTEC does *not* pay to lift water 915 m against gravity — the warm and cold columns nearly balance — so  $H_{\text{loss}}$  is dominated by pipe friction. This is why CWP design centres on maximizing diameter to minimize velocity (and thus friction, which scales with velocity squared) for a target mass flow.

Because each unit of net power requires moving roughly 3–4  $\text{m}^3/\text{s}$  of cold seawater per megawatt, a 35  $\text{MW}_{\text{net}}$  module circulates on the order of 120  $\text{m}^3/\text{s}$  of deep water — flow rates comparable to a small river. Sizing the CWP to keep velocity near 2 m/s drives pipe internal diameters into the 8–10 m range for the largest single-platform modules; composite (FRP) pipe is favoured for its strength-to-weight ratio and corrosion immunity over the 20 year service life.

## 6 Deployment Ramp and Cluster Output

The TROIB Gulf zone scales from a single demonstration-scale module to a ten-platform cluster. Table 2 summarizes the illustrative gross/net trajectory; the constant  $\approx 30\%$  parasitic fraction reflects the assumption that per-module CWP and exchanger design is replicated rather than re-optimized at each step.

**TABLE 2** – Illustrative Gulf-zone OTEC deployment ramp.

Milestone	Platforms	Gross power	Net export	Net fraction
Year 3 (demo module)	1	50 MW	35 MW	70 %
Year 6 (early cluster)	4–5	230 MW	160 MW	70 %
Year 10 (full cluster)	10	500 MW	350 MW	70 %

At full build the cluster contributes the OTEC share of the TROIB ten-year target of  $\approx 1,100$  MW of clean power across all three zones. Net power that is not consumed by co-located AI compute is routed to electrolytic production of green hydrogen and ammonia for export, converting otherwise-stranded offshore capacity into a shippable energy product.

## 7 Nomenclature

$\eta_{\text{Carnot}}$	Ideal Carnot thermal efficiency (dimensionless)
$T_{\text{warm}}$	Warm-reservoir absolute temperature (K)
$T_{\text{cold}}$	Cold-reservoir absolute temperature (K)
$\Delta T$	Surface-to-deep temperature difference ( $^{\circ}\text{C}$ / K)
$\dot{W}_{\text{turbine}}$	Gross turbine shaft power (W)
$\dot{m}_{\text{NH}_3}$	Ammonia working-fluid mass-flow rate (kg/s)
$\Delta h$	Enthalpy drop across the turbine (kJ/kg)
$P_{\text{gross}}$	Gross generator electrical output (W)
$P_{\text{net}}$	Net exportable electrical power (W)
$P_{\text{cwp}}$	Cold-water-pipe pumping power (W)
$Q$	Volumetric seawater flow rate ( $\text{m}^3/\text{s}$ )
$H_{\text{loss}}$	Total dynamic head loss (m)
$U, A$	Overall heat-transfer coefficient ( $\text{W}/\text{m}^2\text{K}$ ), area ( $\text{m}^2$ )

## 8 Selected References (illustrative)

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