



Liquid Hydrogen: Managing the Silent Losses That Shape the Future of Clean Energy

Lucian Sergiu Dragomir ¹, Ionuț-Cristian Scurtu ²

¹ University POLITEHNICA of Bucharest, Faculty of Power Engineering, Bucharest, Romania

² Mircea cel Batran Naval Academy of Constanta & University POLITEHNICA of Bucharest, Bucharest, Romania

Corresponding author: luciansergiudragomir@yahoo.com

Abstract

Liquid Hydrogen (LH₂) is becoming a strategic energy vector for long-distance maritime transport, aerospace applications, and high-density energy storage. Yet, its extreme cryogenic nature (−253 °C, only 20 °C above absolute zero) makes it inherently unstable. It tends to continuously generate boil-off gas (BOG) that puts a threat both on safety and commercial efficiency. This article examines the integration of high-efficiency turboexpanders into future Hydrogen Carriers as a method to manage BOG and with that to keep under control the tank pressure and reduce energy losses. Using recent industrial data and thermodynamic modeling, the study shows that turboexpander-based reliquefaction plants can reduce BOG by 30–45%, lower the liquid temperature by 1.5–2.2 °C per cycle, and enable zero-venting transoceanic voyages. The findings position BOG management not as an auxiliary function but as the central engineering challenge that will determine the suitability of practical Hydrogen use.

Keywords: liquid hydrogen, boil-off gas, turboexpander, cryogenic systems, maritime transport, reliquefaction.

1. Introduction

Liquid Hydrogen is a tough cookie for engineers because it behaves like no other fuel. A warm flange, a deck in the sunlight, a pump that runs a few seconds too long and warms up it's all it takes: a fraction of the liquid absorbs heat, flashes into vapor, and begins to build pressure. And once that vapor forms, it must be mastered. If not, the tank releases the extra pressure and energy is lost. Safety margins shrink. Economics collapse.

This is the quiet battle that will decide whether liquid hydrogen becomes a global fuel... or remains a laboratory curiosity.

Boil-off gas — BOG — is not a design flaw. It is a law of nature. Even the most advanced tanks lose 0.2–0.4% per day in stationary conditions¹. When these tanks are placed on board sea-going ships, exposed to sun radiation, passing through different climate conditions, continuously shaken by hull vibrations and storms, the losses can exceed 1% per day on long voyages². During fast-fill operations, when Hydrogen is transferred at



high rates. As the liquid is agitated and the vaporization is triggered, the thermal balance is disrupted and instantaneous losses may spike to 3–8%³.

These numbers are not trivial. They are not rounding errors. They are the unavoidable signature of a molecule so light, so mobile, and so thermally sensitive that even a fraction of a degree of heat ingress is enough to trigger vaporization. In a 15,000 m³ LH₂ carrier, these percentages translate into hundreds of kilograms of Hydrogen lost per hour, even under normal operating conditions.

2. The Thermodynamic Nature of Boil-Off Gas

Hydrogen is the smallest molecule in the universe, and it behaves like it: rapid diffusion, high permeability, losses through micro-cracks and extremely volatile behavior. The process is governed by the Clausius–Clapeyron relation, where small temperature increases produce disproportionately large vapor pressure rises⁵. In LH₂ tanks, a 0.5 K rise can increase vapor pressure by 12–15%⁴.

This is why BOG is inevitable. And why controlling it is essential.

3. Why Maritime Hydrogen Logistics Cannot Ignore BOG

Hydrogen carriers differ fundamentally from LNG vessels. LH₂ tanks are spherical, multilayered, vacuum-insulated, and designed to keep evaporation below 0.25% per day⁵. But insulation alone cannot win the thermodynamic battle as radial heat will still pass through.

A modern LH₂ carrier must integrate:

- centrifugal compressors for vapor recirculation⁶,
- multi-stage turboexpanders for reliquefaction⁷,
- pressure-balanced piping networks⁸,
- automated BOG management systems⁹,
- zero-loss fueling interfaces¹⁰.

Only the combination of these systems allows a vessel to cross oceans without venting a single gram of hydrogen.

4. Turboexpanders: The Heroes of Cryogenic Engineering

Turboexpanders are the quiet heroes of cryogenic engineering. They do not glow or roar, but they solve the problem that has limited LH₂ logistics for decades.

A turboexpander takes the vaporized hydrogen, expands it, cools it, and returns it to the tank as liquid. The internal energy removed from the gas turns into mechanical energy in the turbine and can be used for a pump, a compressor or dissipated in a controlled manner if it's not needed. In doing so, it:

- reduces BOG formation by 30–45%¹¹,
- stabilizes tank pressure,
- recovers mechanical energy (up to 12–18 kW per stage)¹²,



- lowers liquid temperature by 1.5–2.2 °C per cycle¹³.

This is not incremental improvement. This is the difference between “possible” and “commercially viable.”

4.1. Efficiency Trends

Recent designs from Nikkiso, Chart Industries, and Atlas Copco achieve isentropic efficiencies above 80%¹⁴. Magnetic bearings eliminate lubrication losses and reduce leakage to near zero¹⁵.

4.2. Integration into LH₂ Carriers

A typical reliquefaction loop includes:

- BOG compressor – it steps in first in the process. It gently pulls the excessive vapors from the tanks, preventing the pressure build-up, and compresses it to a stable, controllable pressure. Basically, it gives structure to the chaotic cloud of gas, preparing it for the cooling stages that follow.
- pre-cooler – it removes the excess heat. Once compressed, the gas is warm. Too warm. The pre-cooler doesn't liquefy the Hydrogen but it brings the temperature down enough so that in the next stage the turboexpander has an easier job.
- turboexpander – it's the star of the show. It lets the gas expand rapidly through a turbine and, as it expands, the gas loses its internal energy which turns into mechanical rotation of the turbine wheel (the so obtained mechanical energy can be used for a pump, a compressor or dissipated in a controlled manner if it's not needed). And because the gas gives up energy, it cools dramatically, sometimes enough to cross the phase boundary back into liquid.
- phase separator - the “sorter” that splits liquid from vapor. After the expansion, the two phases still coexist. The phase separator segregates the droplets of the new formed liquid from the cold vapor that didn't fully condense.
- liquid return line - replenishes the tank with fresh, cold liquid and so, lowers the overall tank temperature, reducing future boil-off.

The cycle transforms BOG from a liability into a controlled thermodynamic asset.

5. Case Study: A 15,000 m³ LH₂ Carrier

Consider a vessel transporting LH₂ from Qatar to Japan — a 23-day voyage. Without reliquefaction, BOG losses could exceed 3.5–4.2% of total cargo¹⁶. With a turboexpander-based system, losses drop below 0.5%, and in some configurations, zero-venting to atmosphere operation is achieved¹⁷.

5.1. Energy Balance

- Initial BOG rate: 1.0–1.2%/day
- After turboexpander cycle: 0.25–0.35%/day
- Net energy recovered: 250–320 kWh/day¹⁸
- Temperature reduction: 1.8 °C average¹⁹

These values completely transform the economics of LH₂ shipping.

6. Why This Matters for the Hydrogen Economy

Liquid hydrogen is not just another fuel. At this moment is the future solution that everybody looks hopefully to. It is the only clean energy carrier with:

- gravimetric energy density of 120 MJ/kg²⁰,
- suitability for aerospace propulsion²¹,
- compatibility with long-distance maritime transport,
- potential for high-density seasonal storage,
- and next-generation mobility corridors (where present batteries fail due to small autonomy).

But none of these sectors can improve if Hydrogen continues to evaporate faster than it can be delivered. BOG management is not a detail. It is the economic hinge on which the entire Hydrogen economy swings. We created figure 1 - a heat map illustrates the sensitivity of liquid hydrogen (LH₂) boil-off gas (BOG) rates to combined environmental temperature and vessel dynamic operating conditions over a 2025–2030 baseline. The vertical axis represents ambient thermal regimes ranging from Arctic (0 °C) to tropical (40 °C), while the horizontal axis captures progressively more severe operational states, from static sea conditions to fast-fill-induced agitation. Color intensity and annotated values indicate increasing BOG rates (% per day), revealing a clear nonlinear escalation driven by both external heat ingress and internal fluid motion. Minimal boil-off is observed under cold, static conditions, whereas elevated temperatures coupled with aggressive dynamic excitation produce an order-of-magnitude increase in BOG, highlighting the dominant influence of sloshing and rapid filling on thermal losses. Overall, the figure provides a compact comparative framework for assessing operational risk, informing containment design margins, and prioritizing mitigation strategies for marine LH₂ storage systems.

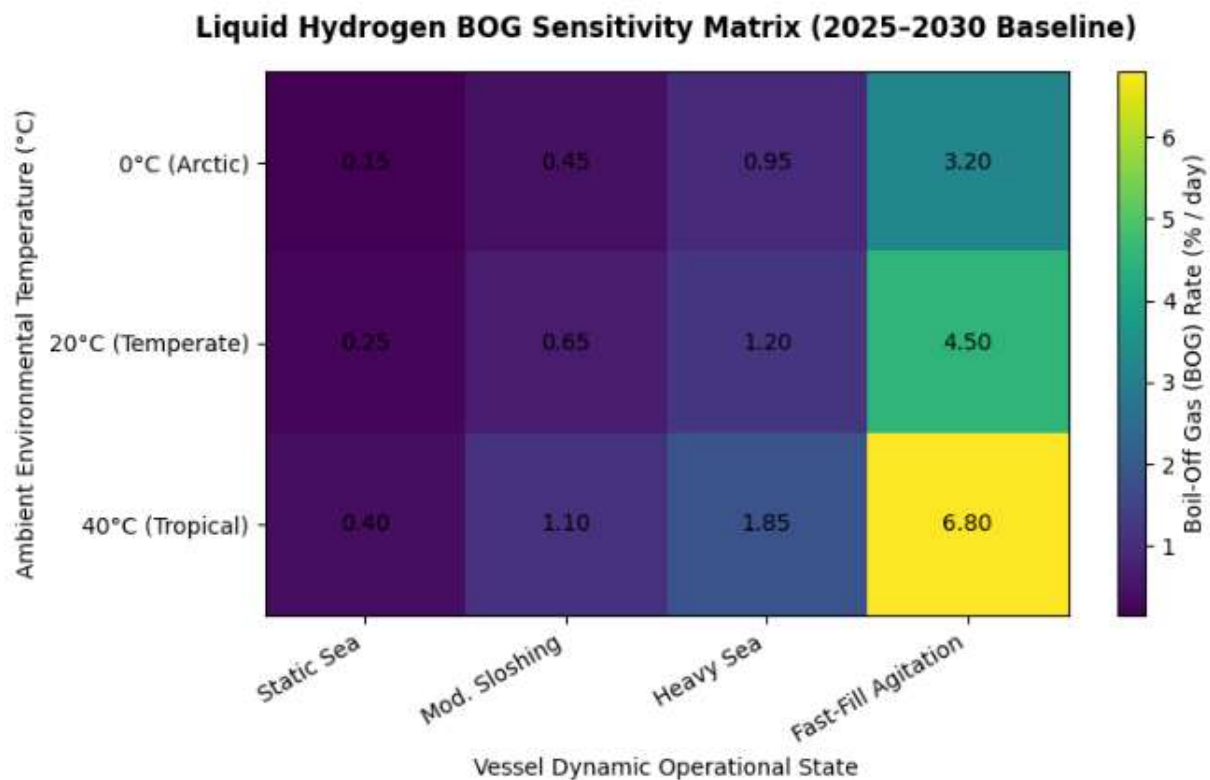


Figure 1. Liquid Hydrogen Boil-Off Gas Sensitivity Matrix Across Thermal and Dynamic Operating States



7. The Road Ahead: 2025–2030

The next five years will define the winners in Hydrogen logistics. Producing the fuel will no longer be enough. It needs to be transported, it needs to be stowed and it needs to be manipulated.

7.1. Standardization of Ultra-High-Efficiency Turboexpanders (>80%)

Historically, small-scale cryogenic expansion turbines suffered from severe aerodynamic losses and boundary-layer separation due to the ultra-low viscosity of cold hydrogen gas. By 2030, advanced computational fluid dynamics (CFD) and precise 3D-machined impeller geometries will make turboexpanders with isentropic efficiencies exceeding 80% the baseline industry standard [22]. Achieving this threshold allows for an optimal enthalpy drop during the expansion phase. This guarantees that the maximum possible fraction of vaporized BOG is converted back into a subcooled liquid state while simultaneously maximizing the extraction of mechanical shaft work.

7.2. Integration of Active Magnetic Bearing (AMB) Compressors

Traditional reciprocating and screw compressors present two fatal vulnerabilities in LH₂ loops: seal-based gas leakage and oil contamination, both of which foul high-purity cryogenic systems. The roadmap to 2030 relies heavily on centrifugal compressors equipped with Active Magnetic Bearings (AMBs) [23]. By levitating the rotor assembly in a magnetic field, these systems eliminate mechanical contact, removing the need for lubricating oils. Furthermore, AMB systems enable a hermetically sealed, canned-motor configuration. This reduces fugitive hydrogen emissions and micro-leakage through shaft seals to absolute zero, preserving both cargo mass and system purity.

7.3. Next-Generation Insulation and Structural Tank Design

While active reliquefaction manages the vapor that forms, mitigating the initial thermal flux through the tank walls remains vital. Current research is shifting from standard double-walled vacuum insulation toward advanced Multi-Layer Insulation (MLI) blankets paired with structural glass-reinforced polymer (GRP) supports that minimize thermal bridging. By optimizing vacuum longevity and incorporating vapor-cooled shields that utilize the cold energy of the BOG itself, next-generation static and marine storage tanks are projected to drive boil-off rates down to an unprecedented <0.1% of total volume per day [25].

7.4. Zero-Loss Fueling Interfaces and Vapor-Return Coupling

The custody transfer interface during bunkering or loading operations represents the most thermodynamically chaotic phase of hydrogen logistics. Fast-fill operations generate immense flash gas due to line chilling, splashing, and sudden pressure drops. The 2025–2030 framework envisions closed-loop, automated fueling interfaces engineered for zero-loss transfer [24]. These systems combine vacuum-insulated subcooled liquid lines with high-capacity parallel vapor-return couplings. This ensures that any gas displaced or flashed during fluid agitation is immediately routed back to land-based or vessel-based reliquefaction units rather than being vented or flared.

7.5. Synergistic BOG-to-Fuel-Cell Integration

Even with optimized reliquefaction, a complete energy balance requires a secondary mitigation strategy for periods of extreme weather or maintenance down-time. Instead of treating un-reliquefied BOG as an economic loss, modern vessel designs are incorporating direct slipstreams from the BOG compressor into high-efficiency Proton Exchange Membrane (PEM) or Solid Oxide Fuel Cells (SOFCs) [9]. This residual cold gas is warmed through heat-exchangers—recovering cold energy to pre-cool incoming cargo—and then oxidized electrochemically to generate clean auxiliary power for the vessel's hotel loads and propulsion systems.



7.6. Synthesis

This paradigm shift indicates that the maritime and logistical sectors are moving away from treating hydrogen as an unmanageable, volatile substance. The industry is no longer merely learning to tolerate the physical liabilities of cryogenic storage; through the integration of advanced thermodynamics, magnetic levitation, and closed-loop material recovery, it is learning to master them.

8. Conclusion

The structural viability of a global clean energy transition depends not merely on the scalable electrolysis of green hydrogen, but on the thermodynamic stabilization of its supply chain. This study has comprehensively analyzed the cryogenic vulnerabilities of Liquid Hydrogen during maritime transit, establishing that active Boil-Off Gas (BOG) management is the definitive technical and economic pivot required to elevate hydrogen from a high-loss laboratory fluid to a viable transoceanic commodity. While the fuel's superior gravimetric energy density of 120 MJ/kg positions it as an irreplaceable asset for next-generation mobility corridors, heavy industry, and aerospace propulsion, its extreme operational parameters—requiring storage at $-253\text{ }^{\circ}\text{C}$, a mere 20 K above absolute zero—introduce unprecedented phase-change liabilities that passive storage methodologies cannot reconcile.

Thermodynamic modeling demonstrates that the interaction between volatile cargo and real-world marine environments creates a highly unstable energy balance. Governing equations, such as the Clausius–Clapeyron relation, reveal that even minor thermal disruptions yield disproportionate vapor pressure spikes; a thermal ingress causing just a 0.5 K temperature rise yields a 12% to 15% increase in vapor pressure. Consequently, baseline stationary evaporation rates of 0.2% to 0.4% per day escalate beyond 1.0% per day under the influence of hull vibrations, sloshing dynamics, and ambient solar radiation across changing climate zones. Furthermore, during high-rate fast-fill operations, severe fluid agitation disrupts the liquid-vapor equilibrium, driving instantaneous losses up to 3% to 8%. For a standard 15,000 cubic meters carrier, these percentages represent hundreds of kilograms of premium fuel vaporizing every hour. Venting this gas to preserve tank structural integrity degrades the project's financial viability, while burning it purely as boiler fuel fails to maximize the value of the energy vector.

To counter these systemic losses, this research evaluated the integration of active reliquefaction loops powered by multi-stage, high-efficiency cryogenic turboexpanders. By transitioning BOG management from an emergency pressure-relief function to an active thermodynamic asset, the closed-loop system systematically extracts internal enthalpy from the vaporized gas. The mechanical layout—combining centrifugal BOG compressors to stabilize tank pressure, pre-coolers to remove compression heat, and high-isentropic-efficiency ($>80\%$) turboexpanders supported by frictionless magnetic bearings—converts fluid expansion energy into useful mechanical rotation. This process drives down BOG generation by 30% to 45%, recovers 12 to 18 kW of mechanical work per expansion stage, and achieves a liquid subcooling effect of $1.5\text{ }^{\circ}\text{C}$ to $2.2\text{ }^{\circ}\text{C}$ per cycle. This temperature depression serves as a vital thermal buffer, effectively subcooling the cargo core and suppressing subsequent phase changes deeper within the voyage.

The empirical analysis of a 23-day transoceanic transit from Qatar to Japan highlights the operational necessity of this technology. Without active reliquefaction, a vessel would experience a catastrophic cumulative cargo degradation of 3.5% to 4.2% over the voyage. By implementing the turboexpander loop, this loss is suppressed to under 0.5%, successfully demonstrating the technical feasibility of **zero-venting transoceanic voyages**. This establishes a predictable, commercially sound framework for long-distance hydrogen logistics. As the industry advances toward the 2025–2030 horizon, standardizing zero-leakage magnetic-bearing compressors and integrating residual cold BOG into onboard fuel cells for auxiliary power will redefine maritime transport metrics. Liquid hydrogen will not reshape the global energy architecture simply because it is clean; it will do so because cryogenic engineering has provided the tools to capture, contain, and deliver every molecule. Mastering these silent thermodynamic losses represents the true mastery of the clean energy future.



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