

Smart management of boil-off gas across the LH₂ supply chain

Low-carbon hydrogen is positioned to play a key role in the energy transition. It is required to decarbonise the production of fertilisers and chemicals, in oil refining, and potentially also for new hard-to-abate sectors in which electrification is not possible or is prohibitively expensive to achieve at scale. Liquefied hydrogen (LH₂) shows potential for large-scale global and regional energy supply [Ref 1–3],* but will require smart supply-chain integration including hydrogen (H₂) boil-off gas (BOG) management. Several BOG management options are available for implementation today, and additional options are being studied, developed and demonstrated. These strategies (Figure 1) aim to minimise the formation of BOG, reliquefy it, and use the recovered gas to benefit the wider supply chain. By selecting a combination of strategies to fit the specific conditions of each supply chain, future projects will be able to manage BOG in a smart and commercially responsible way.

Introduction

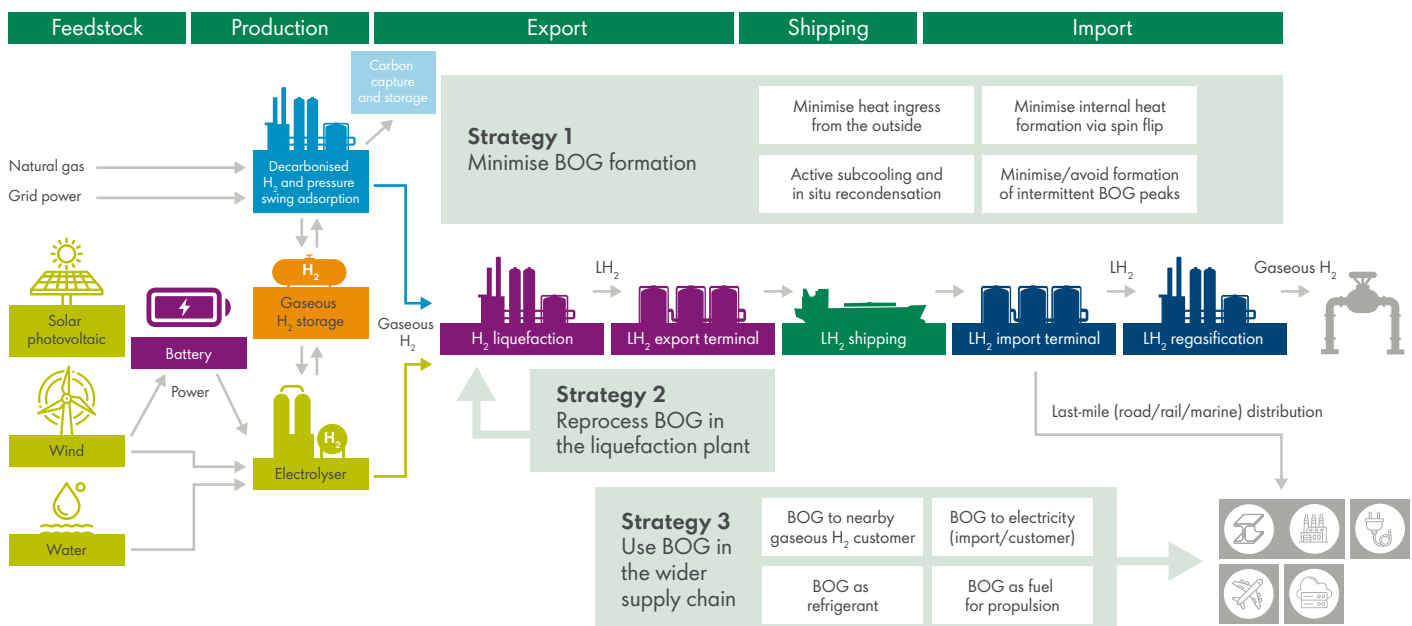
In the context of the energy transition, novel storage and supply technologies are continually being developed and commercialised to enable the global use of low-carbon molecules and energy sources. To successfully commercialise low-carbon H₂ energy supply chains, whether in pure (e.g., liquefied or as compressed gas) or chemically converted forms (e.g., ammonia, power-to-X fuels or liquid organic hydrogen carriers), industry stakeholders need to balance several different challenges across the integrated supply chain. These challenges include achieving a commercially viable levelised cost, energy efficiency and carbon intensity; adherence to regulations, codes and standards; product quality; the health, safety and environmental risk profile; and the reliability of supply.

focuses on H₂ BOG management. Vaporisation of LH₂ is caused foremost by heat ingress from the environment, but flashing, sloshing, stratification or pumping of LH₂, and *ortho*-H₂ to *para*-H₂ isomer conversion (Figure 2), also affect vaporisation rates [Ref 4, 5]. The formation of BOG is considered a key challenge for LH₂ supply chains, and some consider this phenomenon detrimental to the (commercial) viability of this supply option [Ref 6, 7]. Poor BOG management does indeed yield higher H₂ losses, which impact the LH₂ levelised cost, increases the carbon (equivalent) intensity of the supply chain and may introduce process safety risks. Yet, Shell Projects & Technology, along with Shell International Trading and Shipping Company Ltd (STASCO), is observing and participating in a broad cross-discipline R&D and demonstration effort to develop options to enable the smart and commercially responsible management of BOG.

FIGURE 1
Typical building blocks of the LH₂ supply chain and strategies for BOG management.

LH₂ shows potential for large-scale, that is, 100 tonnes per day (TPD), global and regional energy supply. A key aspect in realising this is smart supply chain integration. This paper specifically

*A detailed reference list can be found in [Appendix A](#) on the *TechXplorer Digest* website.



This paper discusses several strategies developed in academia and industry (including at Shell) to minimise BOG formation, to reprocess BOG in the hydrogen liquefier and to seek beneficial BOG use within the wider supply chain. It compares the benefits and drawbacks of several of these strategies.

Minimising BOG formation

The obvious primary strategy in smart H₂ boil-off management is to minimise the formation of BOG in the first place. This starts with the selection of equipment and piping spools that minimise heat ingress, via conductivity, convection and radiation, by offering excellent insulation properties. Vacuum-insulated piping (VIP) and (perlite-filled) vacuum-insulated LH₂ tanks and cold boxes are established technologies with many years of operational reference [Ref 8–10]. See Figure 3 for an example of a VIP schematic implemented by the US National Bureau of Standards in the 1950s.

Vacuum insulation is typically combined with multilayer insulation (MLI) comprising radiation shielding. Solutions are offered by several specialised vendors. The scale and design specifics will determine the actual insulation performance of a system, but it is promising that, for example, HySTRA's 2,250-m³ Hy touch LH₂ tank at the Kobe import terminal achieved a boil-off rate (BOR) of 0.06%/day [Ref 11]. Several other references exist for small (≈ 300–3,000-m³) onshore LH₂ tanks that achieved BORs of < 0.1 to 0.3%/day [Ref 12]. HySTRA's LH₂ carrier Suiso Frontier carries a 1,250-m³ seaborne LH₂ tank with a BOR of 0.3%/day [Ref 11]. Since, theoretically, BOR is proportional to the tank's surface area to volume ratio [Ref 12], the volume scaleup of a specific LH₂ tank design should aid in further lowering the BOR relative to a smaller version of the same design.

Thus, insulation technology R&D and demonstration activities centre on:

- scaleup, and simultaneous cost-down, of VIP spool diameters and LH₂ tank volumes [Ref 13];
- alternative bulk-fill materials in the LH₂ tank vacuum space, such as 3M™ Glass Bubbles or foams [Ref 14];
- liquefied nitrogen (LIN) or BOG vapour-cooled shields (VCS), optionally including an *ortho*-H₂/*para*-H₂ conversion catalyst [Ref 15–17];
- variable-density MLI or layered composite materials [Ref 15];
- nonvacuum insulation concepts (which are more amenable to large, flat-bottom tank designs);
- conversion of onshore insulation designs to concepts suitable for offshore application on LH₂ carriers; achieving BORs of 0.1–0.05%/day is the aim for the large (> 10,000-m³) marine LH₂ cargo containment systems under development [Ref 17, 18].

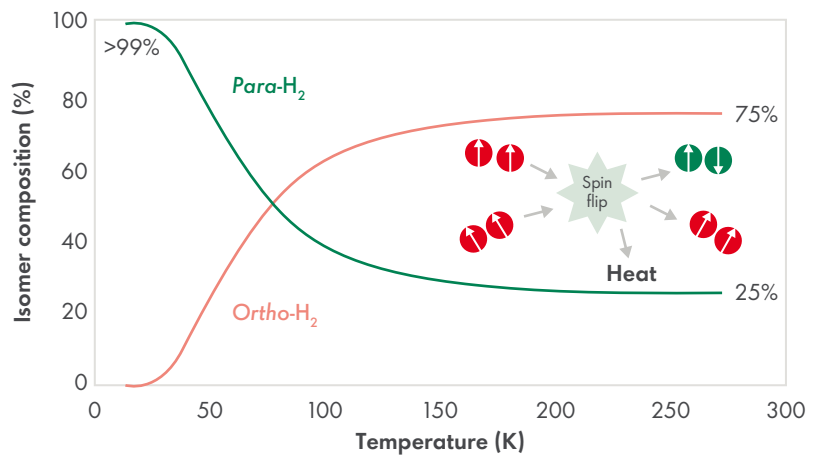


FIGURE 2 Relationship between equilibrium composition of the two hydrogen isomers and temperature. Overlain is a simple illustration of spontaneous conversion of one *ortho*-H₂ (in red) into one *para*-H₂ (in green), releasing heat.

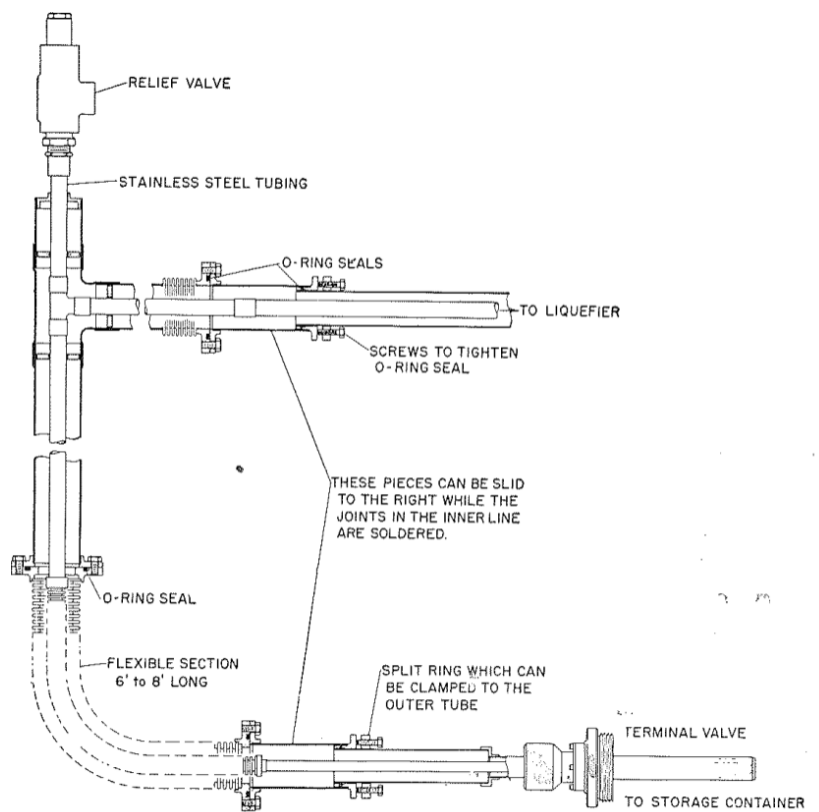


FIGURE 3 Vacuum-insulated piping spool (Source: USA National Bureau of Standards (now NIST), reproduced in Reference 8).

Shell is the leading partner in a US Department of Energy (DoE) project consortium involving CB&I Storage Solutions LLC., GenH2 Corp., the University of Houston and NASA to develop a first-of-its-kind, affordable, large-scale (20,000–100,000-m³) LH₂ storage tank design for import/export applications [Ref 13]. Key success criteria are defined as achieving a maximum LH₂ boil-off rate of < 0.1%/day and maximum capital expenditure < 150% of that of a liquid natural gas (LNG) storage tank of the same volume, and successfully passing a regulatory review on the safety and integrity of the concept under development. Now in its third year, this ▶▶▶

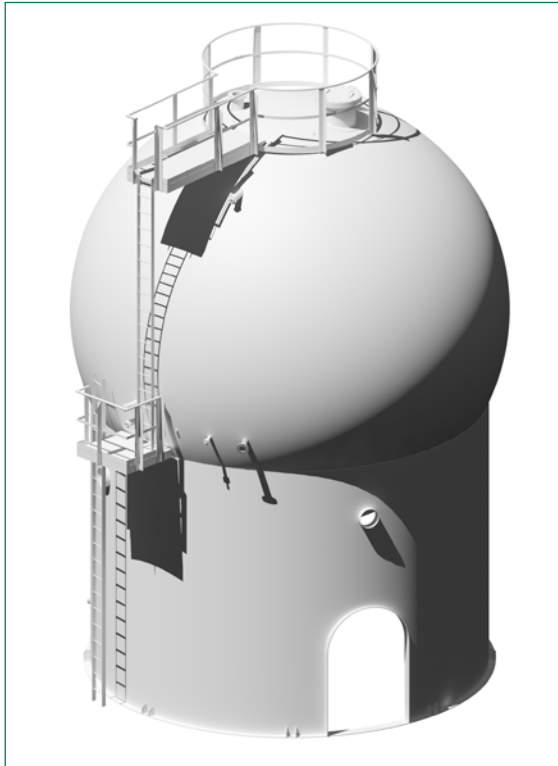


FIGURE 4
Rendering of a 20-m³ LH₂ demo/test storage tank to be located at NASA's Marshall Space Flight Center (source: CB&I).

FIGURE 5
Illustration of the effect of spontaneous *ortho*-H₂ to *para*-H₂ conversion, forming heat, in an adiabatic LH₂ tank/vessel by showing the theoretical LH₂ mass loss curves due to boil-off for two different initial LH₂ compositions: 95% *para*-H₂ and 98% *para*-H₂.

consortium has conducted comprehensive testing and modelling of different insulation materials and designs. The next major milestone in this project is the commissioning of a 20-m³ demonstration LH₂ tank in the spring of 2025, which will enable the testing of nonvacuum insulation concepts in actual daily LH₂ use conditions at NASA's Marshall Space Flight Center (Figure 4).

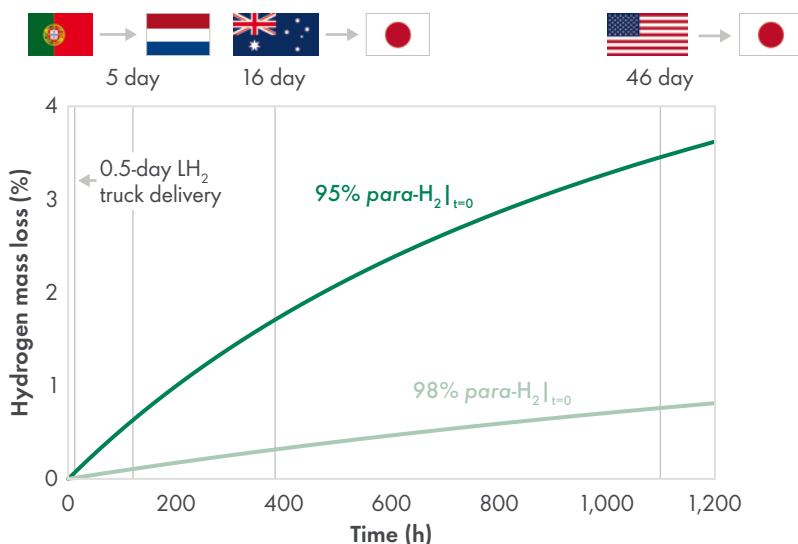
The second approach relates to the unique challenge that hydrogen's two spin isomers (called *ortho*-H₂ and *para*-H₂) pose to LH₂ storage. Normal hydrogen has an *ortho*-H₂ to *para*-H₂ ratio of 3:1, which is the equilibrium composition of hydrogen at T ≥ 230 K. Yet, at deep cryogenic conditions (i.e., T < 25 K), the *ortho*-H₂ to *para*-H₂

equilibrium ratio is 1:99. This change is illustrated in Figure 2.

Inducing *ortho*-H₂ to convert to *para*-H₂ results in an exothermic enthalpy change that exceeds LH₂'s enthalpy of evaporation, or to put it simply: every time one *para*-H₂ molecule forms, enough reaction heat is released to boil off another H₂ molecule [Ref 9]. Operators aim to induce most of this isomer conversion inside the hydrogen liquefier, so as to minimise it occurring spontaneously during LH₂ storage and transport, thus lowering BOG formation during those operations. Typical liquefier designs aim for an ≈ 95% *para*-H₂ LH₂ product specification [Ref 19, 20]. Figure 5 illustrates the boil-off reduction benefit that could be obtained during the extended storage and transport durations typical for global LH₂ supply chains if a ≥ 98% *para*-H₂ LH₂ were produced instead. Indicative shipping durations are provided for LH₂ supply from Portugal to the Netherlands (5 days), Australia to Japan (16 days) and US Gulf Coast to Japan (46 days), respectively [Ref 22, 23].

The third approach is to recondense BOG in situ and/or keep the LH₂ inventory subcooled. A well-known example of this is the integrated refrigeration and storage (IRaS) system, developed by NASA, which was demonstrated in its GODU-LH₂ system and integrated into its new LH₂ tank at NASA's Kennedy Space Center [Ref 24, 10]. This system removes energy from the LH₂ tank using a helium-refrigerant cycle with an internal heat exchanger, thereby reducing or even eliminating BOG formation.

As an example of a similar solution, the company GenH₂ offers its controlled refrigerant transfer system for deployment at LH₂ distribution sites such as hydrogen refuelling stations [Ref 25]. Several variations of the IRaS concept can be devised. An example is changing the refrigeration technology: various suppliers offer small containerised or modular helium or H₂ liquefiers and cryo-coolers [Ref 26–31]. Alternatively, technologies such as magnetic refrigeration may become ready for commercial deployment in the future [Ref 32–34]. Another option is performing BOG condensation in a heat exchanger external to the LH₂ storage tank, then returning the LH₂ to the tank via top spray, bottom or upward discharge filling [Ref 28, 35, 36]. Optionally, some BOG can be routed to a fuel cell or H₂ gas turbine to generate power to drive the refrigerator system and/or surrounding assets [Ref 37, 38]. Figure 6 shows a simple sketch of the IRaS system and some alternative variations. The colours indicate: BOG (light blue), LH₂ (dark blue), warm and cold (helium) refrigerant (light- and dark-green arrows, respectively), and a BOG heat exchanger external to the LH₂ storage tank/vessel (grey). The BOG and LH₂ inventories inside the LH₂ tank are not shown. These solutions are also being



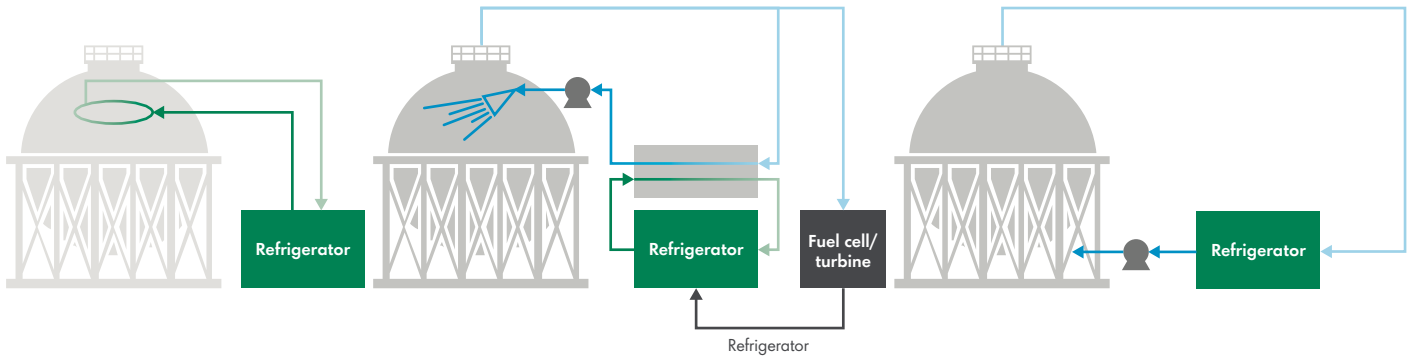


FIGURE 6
Simplified schematics of the IRaS concept (left) and two alternative variations to recondense BOG (middle and right) [Ref 10].

assessed for marine application on, for example, LH₂ carriers or barges [Ref 37, 39].

The fourth approach concerns careful selection of the pressure-temperature conditions across system boundaries in a supply chain (e.g., LH₂ export tank to LH₂ carrier, or LH₂ carrier to LH₂ import tank). This can minimise or avoid the formation of intermittent BOG peak flows that the supply chain then must manage. Let us illustrate this with a simple example.

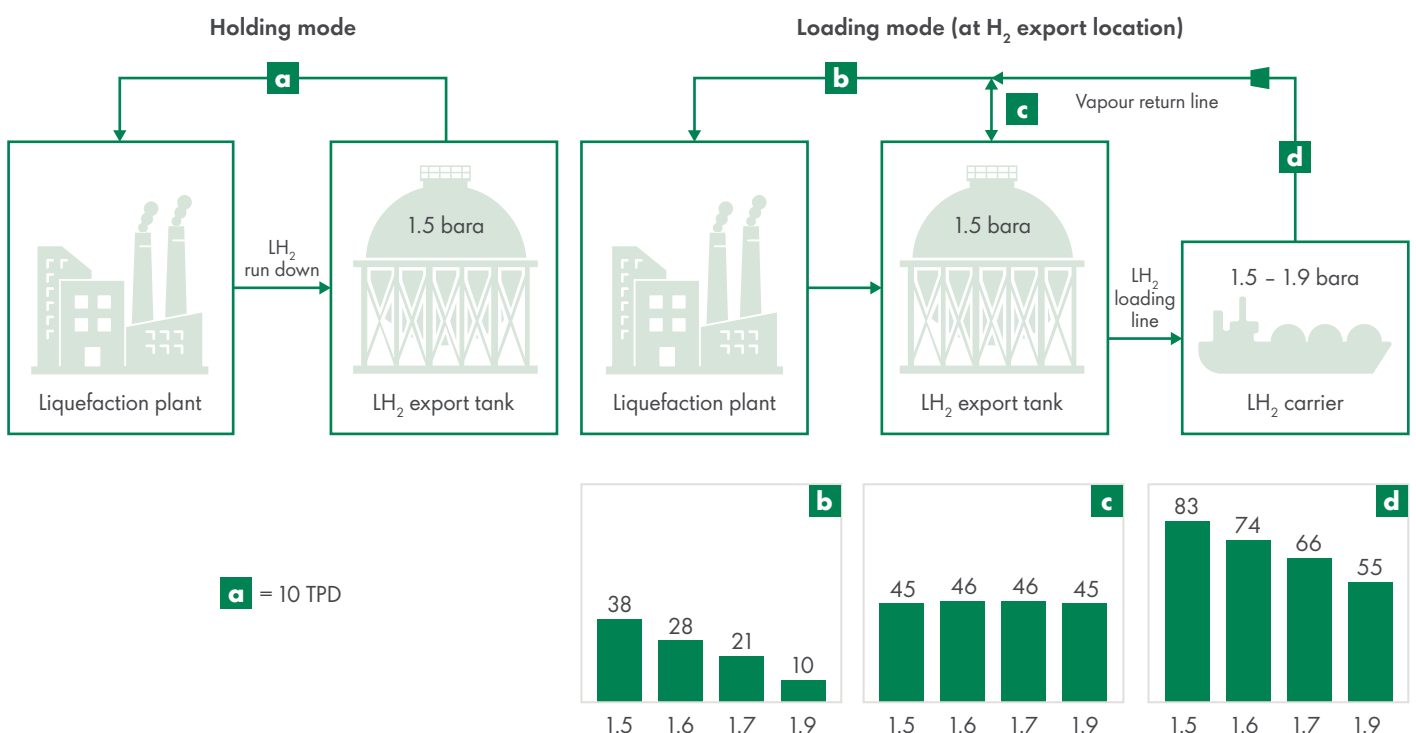
Assume a liquefier continuously runs down its LH₂ product into an LH₂ export tank operated at 1.5 bara. During holding mode, a continuous BOG flow rate of 10 TPD forms in this tank, which is returned to the liquefier for reprocessing (stream a in Figure 7). If, during ship loading mode, this export tank runs down into the LH₂ carrier with the same tank pressure of 1.5 bara, a large BOG flow forms (with a rate of 83 TPD in this case). Just over half of this flow (i.e., 45 TPD) returns to the LH₂ export tank to enable vapour displacement. This leaves a flow of 38 TPD to be sent to the liquefaction plant. This is nearly a fourfold

(temporary) increase of the holding mode BOG flow rate, which the liquefaction plant could struggle to handle.

Yet, if the LH₂ carrier tank pressure is increased, a considerable reduction in BOG formation can be achieved, which directly translates into a lower return flow to the liquefaction plant. The bar charts for streams b, c and d in Figure 7 show this effect. To give an operator the flexibility to select advantageous loading pressures, the LH₂ carrier tanks and associated systems must be designed and safeguarded for a higher maximum working pressure range. This may require installing heavier tanks or allowing a slightly lower LH₂ tonnage onboard.

Figure 7 depicts the results of a simplified LH₂ loading model calculation. For real-world optimisation, such a model must reflect the actual design of the export/import facility and include flashing and all potential sources of heat or energy ingress (e.g., BOG compressors, LH₂ tanks pumps, heat ingress through VIP and LH₂ tanks) and test steady-state and dynamic

FIGURE 7
A simple example showing the BOG flow rates in TPD between a liquefaction plant and LH₂ export tank in holding mode (left side) and between a liquefaction plant, LH₂ export tank and LH₂ carrier during loading mode (right side).



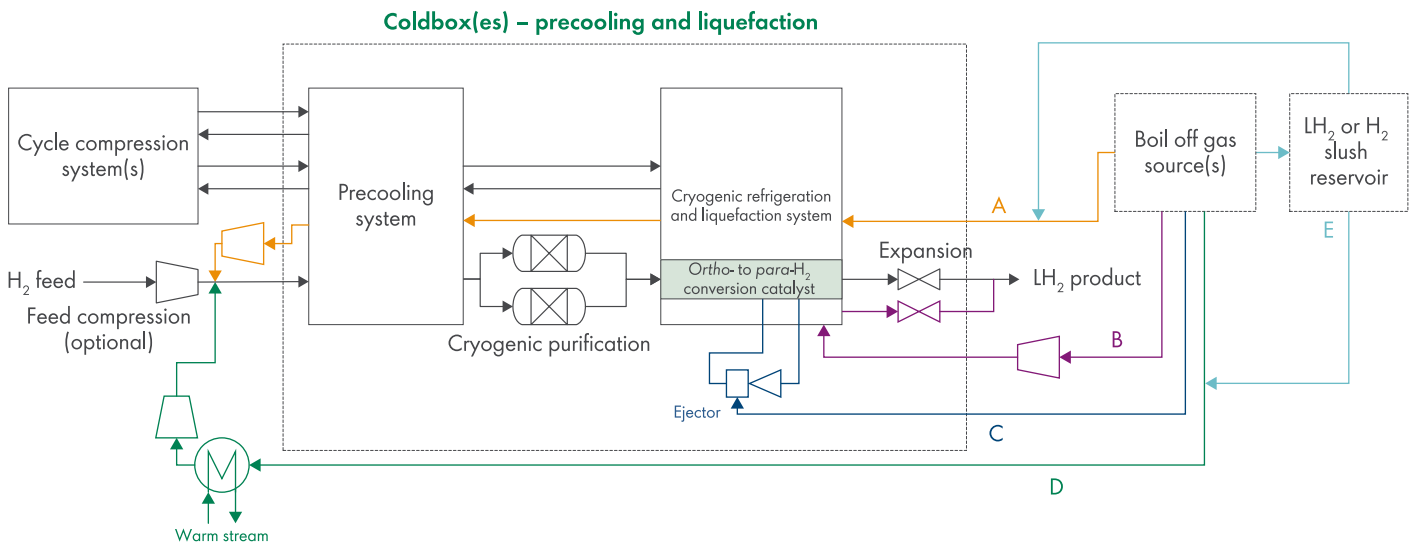


FIGURE 8

Process block diagram showing five strategies to reprocess BOG inside a hydrogen liquefaction plant (source: basic liquefier block diagram is taken from Reference 53 and the strategies from References 19, 42–51, 54, 55).

operational modes. By increasing the LH₂ carrier tank pressure (pressure values underneath the bar charts, in bara), the BOG rate through the vapour return line can be significantly reduced, thereby approaching the lower holding mode BOG rate that the liquefaction plant will easily be able to reprocess. The green trapezoid represents a BOG compressor in the vapour return line.

In some places, BOG forms continuously, at a stable BOR and temperature, while other supply chain locations face short periods of high peak flows. The LH₂ loading operations example in Figure 7 illustrates this. Furthermore, some BOG may have a temperature much higher than the ambient-pressure H₂ boiling point of -253°C . This may, for example, be due to H₂ gas stratification in an LH₂ tank [Ref 4, 40, 41], or occur during the system cooldown mode of LH₂ tanks or carriers.

While this first strategy involves reducing the formation of BOG, the second strategy seeks to use the liquefier asset at the H₂ generation location in an H₂ supply chain to reprocess the BOG.

Reprocessing BOG in the H₂ liquefier

When taking a helicopter view of the options for reprocessing BOG inside the H₂ liquefier plant, five key options emerge (Figure 8).

The first option (A) is to route the BOG stream in the reverse direction (from cryogenic to ambient temperature) through the liquefaction process, enabling it to warm up while valorising its cryogenic cold as if it were an additional refrigerant. Once warmed up to (near-) ambient conditions, the BOG is recompressed and blended with the H₂ feed stream [Ref 42–44]. Variations of this are to blend the BOG into a low-pressure refrigerant return stream on the deep cryogenic side of a pure H₂ refrigerant cycle or to route the BOG in the reverse direction through only part of the liquefaction process [Ref 45].

The second option (B) comprises a cryogenic compressor (either inside or outside the cold box) increasing the BOG pressure, after which the BOG is routed back into the deep cryogenic side of the liquefier for further refrigeration and liquefaction [Ref 46–48]. This BOG compressor may, in principle, be combined with a BOG or H₂ feed/product expander in the form of a compander turbo machine.

The third option (C) passes the cryogenic BOG stream through an ejector or eductor, while using the gaseous H₂ product stream from the cryogenic cold box as the motive (or prime) fluid to pump and recompress the cold BOG and yield a combined pressurised cold H₂ stream. This stream is returned to the cold box for further refrigeration and liquefaction [Ref 19, 49, 50].

The fourth option (D) warms the BOG stream outside the liquefier cold box(es) in a dedicated heat exchanger, followed by BOG recompression at a temperature above -160°C , and typically at (near-) ambient conditions. The compressed BOG is then blended with the H₂ feed stream [Ref 42, 51]. The “warm stream” in this BOG heat exchanger can be ambient air or come from the utility system (e.g., water or steam). Alternatively, the H₂ feed or the liquefier refrigerant stream can function as this “warm stream” before entering the (precooling) cold box, or a compressor chiller stream can be used. This variation yields some valorising of the BOG’s cryogenic cold. Printed circuit heat exchangers seem particularly suitable for such an application, owing to their higher mechanical robustness to larger temperature transients, but other heat exchanger types may also be suitable [Ref 52].

The final option (E) does not strictly reprocess BOG inside the liquefier but may be used to reduce the BOG flow back to the liquefier plant by “peak shaving” large temporary BOG flows stemming from, for example, loading operations. This option

first routes such BOG streams through an inventory of (subcooled) LH₂ or H₂ (slush) ice to recondense a significant portion of the BOG in a dedicated tank system [Ref 41, 54, 55]. This option could be combined with a recondensation line-up, as depicted in Figure 6. The remaining BOG flow must then still be routed to another means of reprocessing or use.

As BOG typically has a high *para*-H₂ content, one could consider including an *ortho*-H₂/*para*-H₂ conversion catalyst [Ref 56] into the BOG channels of the heat exchanger(s) in options A or D to induce endothermic *para*-H₂ to *ortho*-H₂ conversion during BOG warmup and thus increase the cold valorisation benefit [Ref 57].

Comparison of benefits and drawbacks

Options A, B and C seem particularly suitable for handling stable, small BOG flows, and under such conditions offer the benefit of valorisation of the BOG's cold temperature. Brazed aluminium heat exchangers (BAHX) are the common heat exchanger choice for H₂ liquefiers. Sudden, frequent and/or large changes in BOG flow and/or BOG temperature will result in mechanical stress to, and the potential failure of, the heat exchanger core(s). Therefore, the design code limits the maximum temperature change rate and temperature difference between streams, which will be conservative – especially for cyclic transient operation modes [Ref 58].

The benefits of an ejector or eductor component include its lack of moving parts (hence reduced wear and no power consumption), simplicity, small footprint and low investment cost. The main drawback of this component is its narrow operational range and steep performance decline outside of this window. These features make options A to C vulnerable (or even impracticable) in operational modes that result in large and/or rapid changes in flow rate or temperature, for example, the LH₂ carrier loading mode.

Option B also requires application of a compressor system that can handle cryogenic gaseous H₂.

Currently, the use of turbo machinery such as cryogenic H₂ compressors (or companders) is not established, or widely available [Ref 48], so further development, de-risking and demonstration is needed before this option becomes viable for industrial application.

Options D and E seem, in principle at least, suitable for the handling of variable BOG flows. Yet, the low technical maturity and potentially high investment needed for option E raises questions as to its practicability – especially if applied within large-capacity LH₂ supply chains. A summary of these benefits and drawbacks is provided in Figure 9.

Seeking beneficial BOG use in the wider supply chain

While the second strategy can be applied at the H₂ generation location, BOG management options will be required across the overall LH₂ supply chain. For locations that have a nearby gaseous H₂ customer or an available H₂ pipeline grid connection, BOG management becomes less complex. However, this colocation is not always a given. Therefore, the third strategy, of finding alternative uses for BOG, aims to use BOG streams at locations that (1) cannot sell BOG to a nearby gaseous H₂ customer and (2) do not have access to the main H₂ liquefier or to a dedicated, onshore BOG recondensation system.

Here, the first option is to use the BOG as fuel for the propulsion system of an LH₂ trailer truck, LH₂ carrier ship (Figure 10 shows an example design) or an inland waterways LH₂ barge. This idea has been around for decades [Ref 59]. Encouragingly, Approval in Principle was recently granted for the first conceptual LH₂ carrier designs that include power trains capable of running on BOG [Ref 18, 60–62]. Several power train technologies are described (e.g., fuel cells, internal combustion engines or steam turbines, potentially including batteries or dual-fuel capability) [Ref 18, 61–64]. It is likely that systems will be needed onboard to handle any temporary mismatches between the natural rate of BOG formation (nBOR) and

FIGURE 9 Summary of the high-level benefits and drawbacks of the five options to reprocess BOG inside the hydrogen liquefier plant.

	A: BOG as refrigerant	B: Cryogenic compression	C: Ejector	D: External warm up	E: LH ₂ /H ₂ slush reservoir
Valorisation of the cold BOG (for higher power efficiency)	●	●	●	●/●	●
Technically mature	●/● Scale dependent	●/●	●/● Scale dependent	●/●	●
Suitable for stable, small BOG loads	●	●	●	●	●
Suitable for variable BOG loads (temperature, flow)	●	●	●	●	●
Investment	●/●	●	●	●/●	●



FIGURE 10
Rendering of concept design for a 20,000-m³ LH₂ carrier (source: Shell/Houder).

the fuel consumption rate during the voyage and during port stays. For example, when more power is required to reach full sea speed, these could include a vaporiser to ensure sufficient H₂ fuel is supplied to the propulsion system, or arrangements for combustion of a secondary fuel [Ref 62]. Circumstances in which excess BOG is formed may necessitate a BOG reliquefaction system or a dedicated, safe BOG combustion system (typically called a GCU) [Ref 65]. Researchers have even suggested that a ship-to-shore grid connection could monetise BOG formed during port stays by using the vessel's onboard power train system to convert the gas to electricity for export to an onshore grid [Ref 63].

Further techno-economic and carbon-intensity studies are needed to find the optimum solution that balances a carrier's insulation efficiency (and likely higher capital costs), and operational considerations relating to using BOG as a fuel (and electricity source) or handling BOG via reliquefaction. The optimisation will depend on vessel size and journey length [Ref 21, 39], but this is feasible. Similar to the situation for LNG, the optimum may shift in response to future LH₂ market pricing.

The fuel value of BOG could also be used at an LH₂ import terminal or end-user location to generate electricity and power LH₂ pumps, H₂ compressors, utility systems and the control room, or to supply the electricity to an available power grid. Some studies suggest that the cold BOG can be used to increase power production efficiency by, for

example, incorporating organic Rankine cycles using BOG-chilled condensers [Ref 66].

Similarly, BOG could be used to generate electricity at an LH₂-supplied hydrogen refuelling station [Ref 67] (potentially colocated with a truck stop) to power its lighting, facilities, auxiliaries and forecourt and shop heating and air conditioning. This concept could also work for LH₂-supplied inland shipping bunker stations that offer additional services. Taking the typical power consumption of a conventional petrol station in Europe as a reference, a BOG rate of 30–100 kg/day would be sufficient to power such infrastructure [Ref 68, 69]. Another plausible power user at such a location would be colocated electric-vehicle charging facilities for passenger cars or heavy-duty trucks. Both these options require the investment in and installation of a fuel cell system, potentially with a battery storage system (to balance power production with demand) and/or a grid connection.

Finally, there may be opportunities to be found in cold recovery. Real-world examples exist of integration between an LNG supply chain (typically, its regasification system) and another (process) user that needs refrigeration or "cold" [Ref 70]. Several publications propose and/or analyse the different applications (potentially suitable for LNG cold recovery [Ref 71–76]. Figure 11 lists some of these applications. Similar (more detailed) figures can be found in the papers by Atienza-Márquez et al. [Ref 71] and He et al. [Ref 75]. It is not a big leap to see the same potential for cold recovery in these applications using LH₂ and/or cryogenic BOG streams instead of LNG [Ref 77].

Looking to the future, fluids like LH₂ and liquid helium have been proposed or studied as refrigerants for cooling superconducting magnets, wind power generators, aeroplane propulsion systems or power cables [Ref 78–80], and super- to quantum-computing systems [Ref 81]. In principle, cryogenic BOG could be used as a (precooling or secondary) refrigerant stream in the same applications.

For cold recovery to be integrated with an actual LH₂ supply chain project (or LNG project, for that

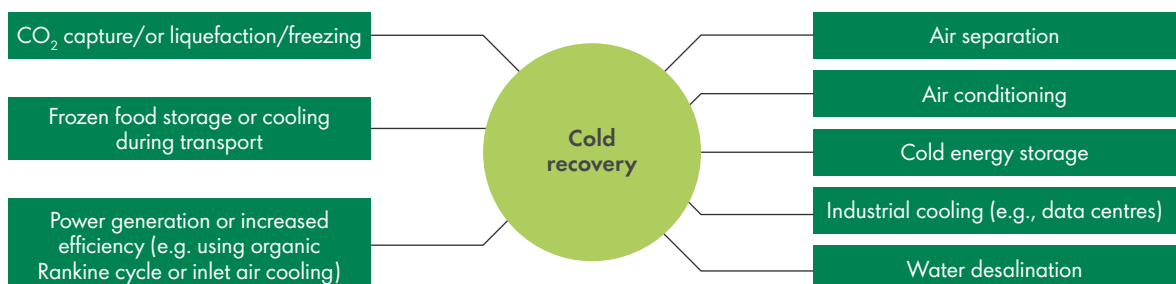


FIGURE 11
A selection of LNG cold recovery applications proposed and/or analysed in the literature [Ref 70–76].

matter), some stars do, however, need to align [Ref 71]:

- colocation of the LH₂/BOG source, with the process user consuming the “cold”;
- reliable and long-term supply (and use) of the “cold” is required;
- a match between the amount of “cold” available (i.e., the temperature and flow rate of the LH₂/BOG stream) and the refrigeration needs of the customer; and
- that the LH₂ supply chain owner and “cold” process user must both have good commercial incentives and be successful in negotiating favourable terms and conditions (including supply guarantees) to enable a satisfactory supply-offtake agreement.

The fact that LNG cold recovery is not yet widely applied shows that, frequently, the stars do not all align, and the same must be expected for LH₂ supply chains. However, some future projects may simultaneously use LH₂ and need cryogenic “cold”. This sector coupling is essential for H₂ supply chains. This would create a situation of colocation, and may simplify the aspects around matching and managing supply and offtake. Think, for example, of (supercomputing) data centres that self-generate electricity from LH₂ [Ref 82–84].

Conclusion

As reprocessing in the liquefier (Strategy 2) or finding alternative uses for the BOG (Strategy 3) will, in most cases, increase the complexity of a supply chain (subsystem) or create new interfaces with systems outside the LH₂ supply chain, smart BOG management should typically start with the minimisation of BOG formation (Strategy 1) in the

first instance. Moreover, the specifics of each supply chain project (such as, LH₂ cost targets, local conditions, requirements of project partners and prospective LH₂ customers, permit requirements and carbon-intensity targets) will inform how much scope, complexity and capital investment can be directed towards these three strategies.

Nevertheless, several BOG management options are available for implementation today, and additional options are being studied, developed and demonstrated. This will enable future projects to manage BOG in a commercially responsible way by selecting a combination of strategies (see Figure 1) and the options therein; technology solutions; and temperature–pressure parameters across the supply chain interfaces that fit their specific conditions and will, indeed, result in smart BOG management.

Acknowledgements

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Review:

This article provides a good overview of the state of the art and potential pathways for the very relevant topic of BOG handling in LH₂ supply chains and LH₂ transfer operations. It is anchored in sound technical and fundamental reasoning, and is very carefully written with remarkable clarity.

Arnoud Higler, Principal Researcher

This content follows Shell’s net carbon footprint and net-zero emissions target principles as documented here: www.shell.com/investors/disclaimer-and-cautionary-note.html.

References

Please refer to [Appendix A](#) on the TechXplorer Digest website.

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