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Capture, storage, and re-use of liquid hydrogen boil-off for aviation and aerospace applications

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Despite major interest in the use of liquid hydrogen as a fuel for aviation and aerospace sectors, loss of hydrogen through boil-off continues to be a hurdle as it causes financial loss, indirect greenhouse gas emissions, and safety concerns. Herein, we perform techno-economic analysis, calibrated with experimental measurements, to assess the use of sorbents to capture and condition hydrogen boil-off events in the range of 1.5 to 70 tonnes per day at launch sites and airports. We evaluate the direct delivery of captured boil-off to combustion engines and fuel cells, comparing against boil-off re-liquification and compression. Results indicate probable cost-effectiveness at delivered liquid hydrogen prices above 0.9 U.S. dollar ($) per kg H_2 at airports, and above 10 $ per kg H_2 at launch sites where 10% or more of hydrogen is lost to boil-off.

One of the largest consumers of liquid hydrogen (LH_2) is the aerospace industry. Historically, the National Aeronautics and Space Administration (NASA) has relied on LH_2 as a propellant for its space missions, using it in combination with liquid oxygen in rocket engines[1,2]. Past 2030, the aviation sector is projected to become a major consumer of LH_2[3,4], with studies estimating that the aviation market could consume up to 8–12% of the global hydrogen energy supply by 2050[5,6]. LH_2 has high energy density per kilogram, and offers a viable alternative to jet fuel thanks to its ability to deliver high thrust while maintaining a clean burn[7,8]. However, storing hydrogen (H_2) as a liquid with temperatures of approximately −253 °C causes hydrogen emissions referred to as "boil-off" over time, with much greater boil-off occurring during transfer events that deliver LH_2 to onboard fuel tanks[9,10]. Hydrogen emissions add to the environmental impact of the industry, with H_2 itself an indirect greenhouse gas emission, ~8.8–11.6 kg carbon dioxide equivalent (CO_2e) per kg of H_2)[11,12]. Aside from the environmental implications, at current H_2 prices in the United States, infrequent refueling events present a financial burden to aerospace customers, with as much as 50% loss of LH_2 to boil-off[13]. In comparison, more frequent refueling at airports may result in boil-off quantities that constrain the use of LH_2 in the aviation sector[14,15]. In order to mitigate these impacts, solutions that reduce boil-off or capture and repurpose it for onsite use are of great importance.

From the perspective of a typical LH_2 supply chain, loss of H_2 occurs during its production, including leakage from electrolyzer, and boil-off during storage, distribution, and at the end-user[10,16,17]. Boil-off from stationary or mobile LH_2 storage tanks poses critical safety risks if not managed through controlled venting[18]. During transfer events (e.g. from stationary LH_2 storage tank to conditioning tank), heat ingress through transfer lines and piping causes LH_2 vaporization[19]. Even precooling of transfer lines with LH_2 cannot completely mitigate heat ingress, with between 10-50% LH_2 boil-off reported during precooled refueling, where the lower bound represents more frequent cycling that would reduce this precooling phase[20]. Additional factors driving boil-off during transfer include pressure changes and selection of insulation materials[10,16,17].

Material-based solutions for boil-off capture have also been proposed, with early references in the 1980s[21], Commonly researched sorbents for hydrogen capture and storage include metal-organic frameworks (MOFs), zeolites, and activated carbons, which all

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primarily operate through physisorption under cryogenic conditions (e.g., 77–270 K). Each material offers distinct structural properties. For example, MOFs have highly-tunable crystalline frameworks, zeolites have relatively more uniform microporous channels, and activated carbon has heterogeneous, hierarchical pore networks[22,23]. In this context, considering the scale of these scenarios, the selection of activated carbon is primarily driven by its technological maturity, market readiness, and robust relative performance. It is a more commercially advanced material that demonstrates comparable adsorption performance to relatively more novel sorbents like MOFs—which have been modelled in our previous studies—making it a strategically more suitable choice for near-term system development[24–26]. However, to our knowledge, there are sparse techno-economic analysis (TEA) evaluating the use of state-of-the-art adsorbent materials under real-world operation cycles plausible in the capturing, storing, and re-using LH_2 boil-off in the aviation and aerospace sector. Tanks packed with sorbent materials have been developed for storing hydrogen and offer fast release kinetics, and favor cryogenic conditions to achieve high hydrogen uptake[27,28]. While cooling hydrogen to ultra-low temperatures for storage in sorbents is not cost-effective, in a boil-off capture application, the gas is already at useful temperatures and purities for sorbents, making sorption-based capture systems a promising candidate for boil-off capture.

While contemporary studies related to LH_2 boil-off have predominantly focused on modeling mechanisms such as leakage-induced boil-off losses or those due to evaporation and sloshing[29,30], the economic feasibility of capturing, storing, and reusing boil-off gases remains relatively underexplored. Once conditioned, boil-off can theoretically be used as a direct fuel for hydrogen combustion engines or fuel cells, or reliquefied. The economic viability of using LH_2 boil-off from bulk storage tanks on ships directly for ship propulsion and electricity generation was estimated to reduce a vessel's total lifetime cost by up to 32%[31,32]. Both launch sites and airports require electricity and fuel, providing various end uses of boil-off that lead to potential recovery of product value. However, the most economical approach for storing and reusing the captured gas remains unclear, which requires careful consideration of factors such as end-use applications, operational conditions, and usage patterns.

In summary, boil-off occurs not only during long-duration storage of LH_2, but also during transfer operations (e.g., from storage tanks to operational tanks or during dispensing), which typically involve high flow rates. Thus, in this study, we perform TEA tailored specifically to evaluating the use of sorbents for capturing, storing, and conditioning LH_2 boil-off under different boil-off event scenarios for aviation and aerospace applications. The cost impacts of key factors such as H_2 use pattern, adsorption uptake, and heat of adsorption or desorption are evaluated. For each boil-off scenario, we investigate the potential of re-using the captured boil-off in an engine or fuel cell as a gas, delivering it to a re-liquefaction system to offset the purchase of LH_2, or delivering to a compression system to offset the purchase of 350 bar compressed gas. For each end-use, the optimum capture and storage conditions that lead to the lowest cost is obtained and used to find the breakeven H_2 cost that makes capturing the boil-off profitable. Lastly, sensitivity analysis is performed to understand the impacts of sorbent cost and target boil-off fraction on potential improvements in H_2 uptake performance. In several scenarios considered, it was found that the costs of LH_2 identified for boil-off capture and re-use result in probable cost savings.

Results and Discussion

Scope, scenarios, and use-cases

Herein, we classify boil-off scenarios, market applications, and end-uses to create prototypical operation cycles for the sorbent storage system and balance of plant based on correspondence with two industry partners: Airbus and Stoke Space Technologies. In this study, "market application" refers to three industrial sectors in which the system is employed—specifically, (1) small and (2) large aviation and (3) aerospace operations of varying scales (Fig. 1a–c). After the H_2 boil-off is captured and stored, it could either be directly used as a gas, or conditioned and stored in a denser manner for future use, as shown in Fig. 2a. We evaluate four types of "end-uses": I-A; direct delivery to an engine; II-A direct delivery to a fuel cell for electricity generation, for propulsion or facility energy use; I-B re-liquification and storage; and II-B compression and storage for longer duration storage. Thus, twelve "boil-off scenarios" (four end-uses for each of the three market applications) are evaluated in this study, including small- versus large-scale consumption of hydrogen, and frequent versus less frequent use (Fig. 1d and e). For small-scale aviation (Fig. 1a), the stored liquid H_2 capacity is 50 metric tonnes, which is sufficient for typical regional or private airport, with a boil-off fraction of 3%. For large-scale aviation (Fig. 1b), the storage capacity is 1,400 tonnes, which could supply roughly one airport terminal, with boil-off rate of 5%. For aerospace (Fig. 1c), the LH_2 storage capacity is 500 tonnes which can supply two of large LH_2 dewars (~ 20,000 m^3) that have recently been built by the NASA, with boil-off fraction of 10%. More details of the scale assumptions can be found in Supplementary Note 1 and Supplementary Table 1. Finally, for all three scenarios, we included sensitivity analysis for boil-off fractions ranging from 0.1% to 30% (*key assumptions*)[9,10,33,34].

Figure 2 shows the integrated framework for evaluating the economic potential of H_2 boil-off capture, storage, and re-use processes, highlighting the key processes and influential factors being considered in this study, as well as representative experimental data for material performance. Table 1 summarizes key operating conditions and reference data used to evaluate hydrogen boil-off capture, storage, and re-use pathways.

Key influential material and system factors affecting cost performance during each stage of the capture, storage, and release are shown in Fig. 2b and the process flow diagram in Supplementary Fig. 1. For example, at the system level, electricity and heat provision and removal required to condition the boil-off H_2 and storage system to the target temperature and pressure are considered. For the sorbent material, aside from cost, the base case H_2 uptake performance is shown in Fig. 2c, and is measured and fitted as described in the *Methods Section*. These results serve as validation of the adsorption model. Other than the uptake, key properties such as pelletization and packing, will affect its system-level performance. For example, near-ambient storage conditions may favor low porosity or denser packing, whereas cryogenic conditions favor higher porosity since the density of LH_2 is already high. Such a difference could lead to up to 50% variation in cost, and volumetric energy density that affects the land footprint[25,26]. Pelletizing and packing patterns of material in tanks can also affect pressure drop and inner-pellet heat exchange efficiency[35,36], which are out of the scope in this analysis but would warrant further investigation.

Optimum conditions for boil-off capture, storage, and re-use

We calculate the levelized costs of H_2 for a range of temperature and pressure conditions for activated carbon, screening for conditions that allow for less than 20 U.S. dollar ($) per kg capture cost (Fig. 3). The optimal operational windows vary by scenario, demonstrating how adsorption capacity and system energy efficiency which are affected by pressure and temperature, jointly determine the economic viability. If the stored boil-off is directed to engines, fuel cells, or to compressed gas storage, there is a wide range of conditions that allow for low-cost capture, with an optimum under high-pressure and near-atmospheric temperature (Fig. 3a, 3c, and 3g and Supplementary Fig. 3). On the other hand, it is more economical to capture and store the boil-off under cryogenic conditions for re-liquefaction (Fig. 3b, 3d, and 3g) to maintain high storage capacity and reduce redundant cooling. As represented by the orange color in Fig. 3, the low-cost regions for

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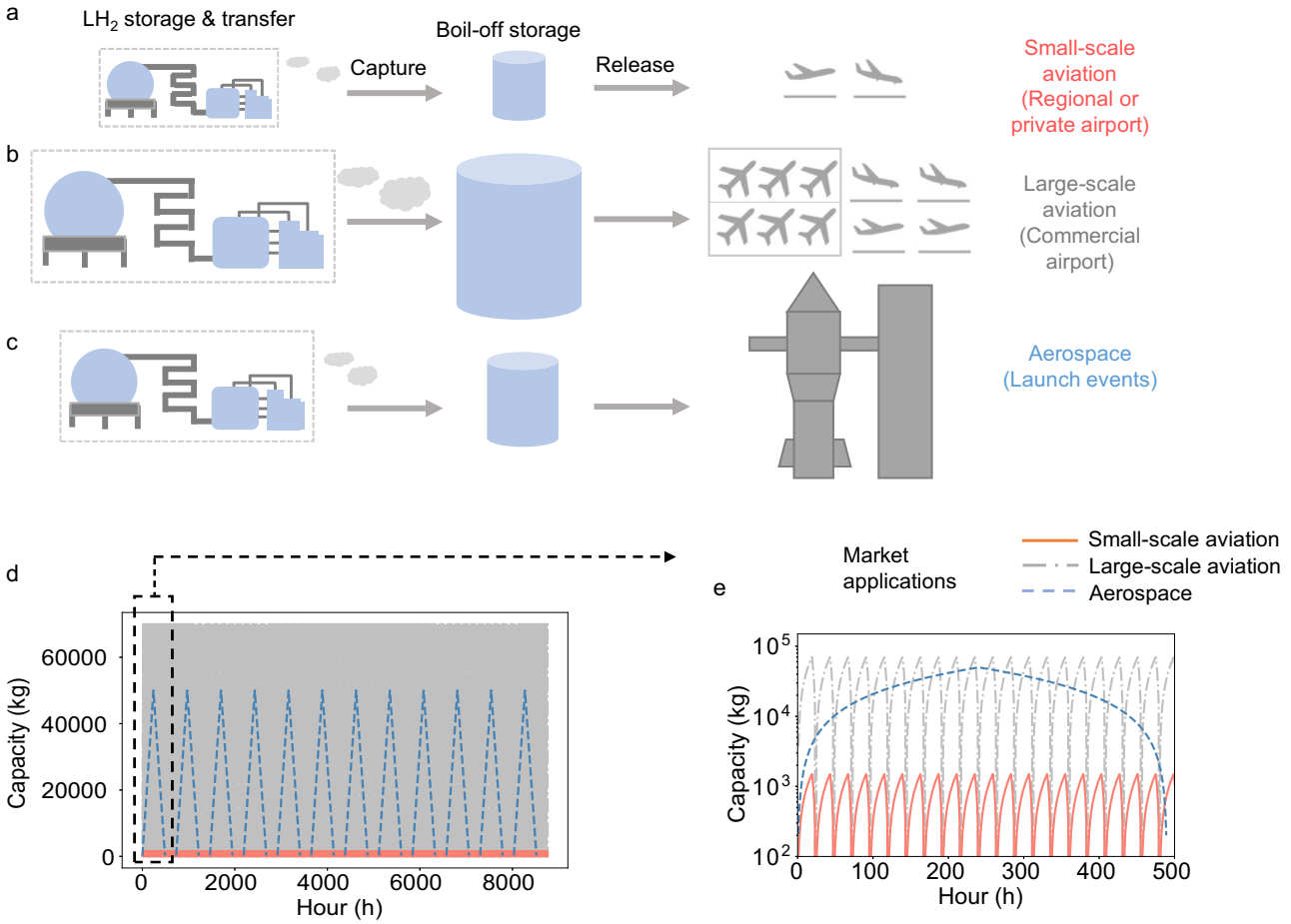

Fig. 1 | Market applications for liquid hydrogen (LH_2) boil-off capture and storage for aviation and aerospace. a–c Schematic diagram of the scenarios. Top to bottom: market application (**a**–**c**). **d**, **e** Equivalent operation patterns of the scenarios: (**d**) per annum and (**e**) per 500 h. Detailed description and supporting references are included in *Methods* and Supplementary Note 1.

releasing the captured LH_2 boil-off to re-liquification are smaller compared to above-ambient temperature and pressure end-uses (engine, fuel cell, and compression). This means that re-liquifying the boil-off has stricter requirements to achieve relatively low levelized cost (capital and operational costs normalized to per kg H_2 stored, details in *Methods*) due to the cooling penalty in terms of cost and energy increases dramatically under cryogenic conditions compared to near-ambient conditions. Specifically, to re-liquefy H_2 under extremely low temperatures and high compression ratios, the coupling refrigeration system requires significantly higher capital investment and energy consumption compared to above or near-ambient processes. The use of multi-stage refrigeration cycles contributes to steep marginal costs, with system complexity, compression work, and heat-exchange duty increasing almost exponentially as the target temperature becomes lower[37,38]. For example, the power required to deliver 1 MW of cooling load increases from 1.9 MW at 223 K to 17 MW at 83 K[38]. As a consequence, the optimum operating region is narrower for this end-use, as it requires a stricter balance between temperature and pressure to maximize the natural cooling effect from gas expansion during boil-off decompression and minimize the need for additional cryogenic refrigeration. Therefore, this implies that future studies should include the additional costs for better system control and thermal integration.

One can observe that since the LH_2 is used less frequently for the aerospace market (Fig. 3e), lower temperature becomes more optimal to capture and store the boil-off for the engine use case. This is because the power of cooling and compressions systems can be reduced simply by reducing charge and discharge rates for less frequent boil-off use. By doing so, the costs are reduced, and the system can afford to operate under lower temperature and higher-pressure conditions, where the H_2 uptakes are higher.

Cross comparison and breakdowns

For the cost values, there are two factors to consider when comparing the scenarios and end-uses in this study. First is the effect of use frequency, as it determines how much H_2 is released per year.

Due to the different frequency assumed in this study the levelized cost of the aerospace sector (in-frequent aerospace launches: 12 per year) is much higher than the aviation sector (frequent airport uses: 365 per year), at approximately 5.7–21.6 $ per kg compared with approximately 0.4–10 $ per kg (lower and upper bounds, detailed operation patterns are discussed in the *Key assumptions* Section). Although cheaper than the aerospace sector, small-scale aviation such as private or regional airport do not display the same benefits from economy of scale as large aviation scenarios which had the lowest cost range (approximately 0.4–3 $ per kg), and is highly sensitive to boil-off end-use selection (Fig. 4a). Like many energy systems with high capital cost, a lower capacity factor increases levelized cost (details in *Methods Section*). Second is the economy of scale, meaning the inverse relation between the cost per functional unit (per MW power and per kg H_2) as scale increases. To provide a better comparison between the cost performances in different scenarios, their optimal cost in Fig. 3 is broken down into Fig. 4.

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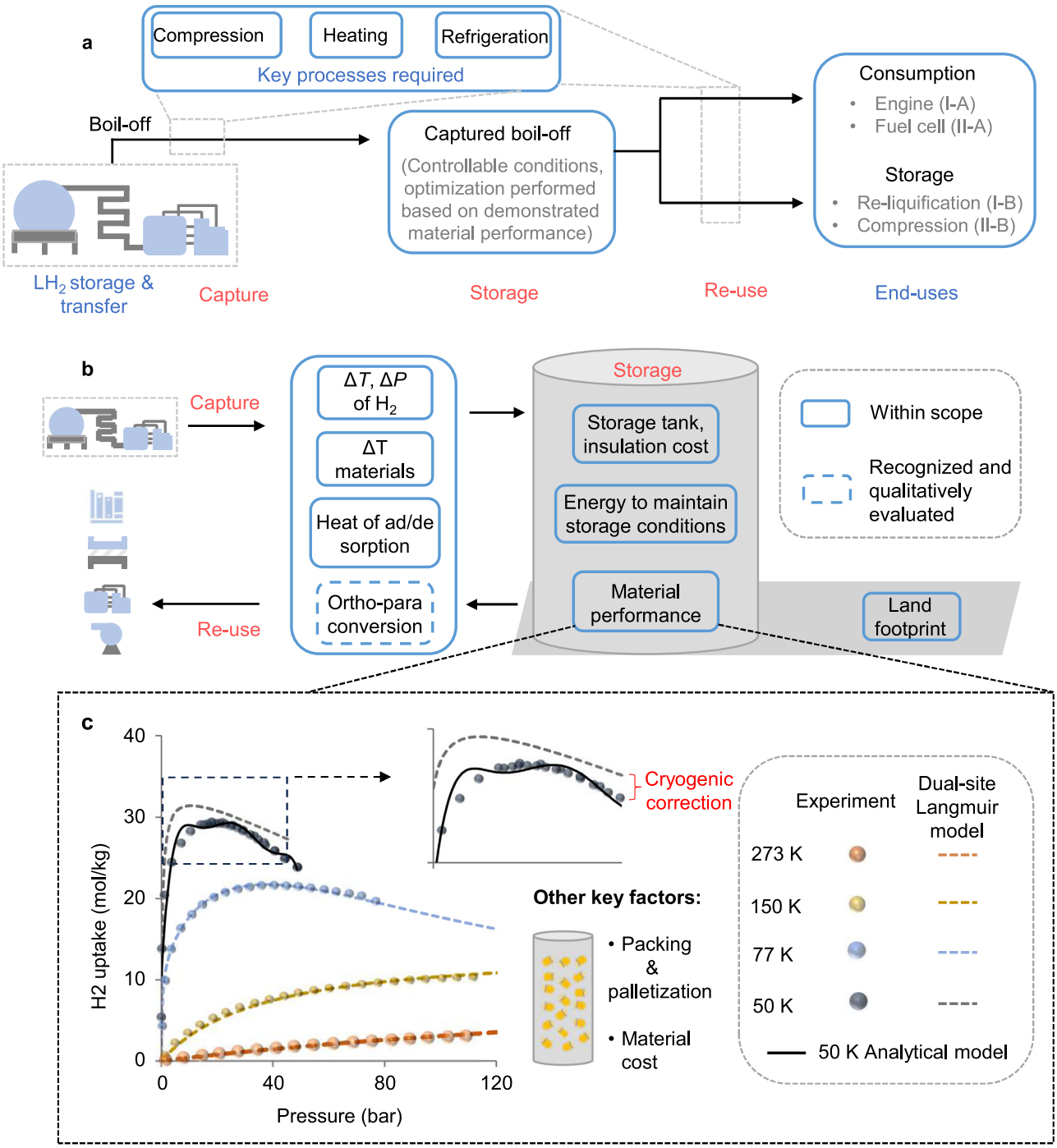

Fig. 2 | Scenarios for liquid hydrogen (LH_2) boil-off capture and storage for aviation and aerospace applications. a Schematic diagram showing the key processes and end-uses. **b** Schematic diagram showing the scope of work, highlighting the main factors considered during the boil-off capture, storage, and release stages. **c** scope of influential parameters for material performance evaluated in this study, along with exemplary H_2 uptake isotherm of the sorbent measured in this study.

In terms of cost breakdown, activated carbon sorbent assumed at 10 $ per kg (a relatively conservative estimate)[39,40] is still the largest capital cost except for re-liquefication, where the refrigeration accounts from 63% to 95% of the capital cost for aerospace and small-scale aviation, respectively. For re-liquefication, refrigeration cost ranges from approximately 0.63-4.7 $ per kg across the three scenarios. This falls in the lower range of recently-reported techno-economic results for direct liquefication from electrolyzers approximately 2.5–9.1 $ per kg[41–43], as boil off is re-liquefied from a low temperature after capture. Note that when capturing the boil-off gas using sorbent, the isosteric heat is negative during adsorption, which leads to unwanted temperature increase if the end-use is to re-liquify the boil-off. As a result, to overcome these and reach the target temperatures, significant refrigeration during adsorption becomes a dominant cost component. Aside from refrigeration, equipment and material-related expenditures, particularly for storage and thermal management, is one of the most expensive components across most scenarios. As shown in Fig. 4d, sorbents, storage tanks, and heaters together account for more than half of total capital costs in nearly all aviation and aerospace cases (over 70% combined for all cases after combined with refrigeration),

Table 1 | Conditions for the market applications and end-uses evaluated in this study

Categories	Hydrogen Condition	References
Boil-off inlet temperature and pressure	40 Kelvin (K), 3 bar	9,33,42,49
Storage temperature and pressure	30 to 298 K, 0 to 100 bar	51–53 and from measurements
Set I, End-use type A - Engine	293 K, 2 bar	62
Set I, End-use type B - Re-liquefication	20 K, 2 bar	63
Set I, End-use type A - Fuel cell	323 K, 2 bar	64,65
Set II, End-use type B - Re-compression	298 K, 350 bar	66

highlighting the importance of cryogenic system design in determining overall economics. Utility costs, including electricity for compressors and refrigeration during both capture and release cycles, contribute substantially to operational expenses, especially under frequent-use conditions where thermal cycling losses accumulate. In contrast, land and insulation costs remain comparatively minor, but their proportion increases at smaller scales (regional airports and aerospace launches), where infrastructure cannot be fully amortized. The tradeoffs between fixed and variable costs show that end-uses requiring high upfront investment, such as re-liquefaction, become more economical when used frequently and at large volumes. In contrast, systems with low use frequency, especially in aerospace applications, end up with higher costs because expensive equipment such as refrigeration and sorbent units are not fully utilized to their largest potential.

Considering both the frequency and economy of scale, large airports could see the lowest levelized cost for a LH_2 boil-off capture to end-use system, at 0.4 $ per kg for fuel cell end-use. This result is highly promising, given current market delivery prices of LH_2 are well above 30 $ per kg in the United States [44]. As the cost savings naturally decrease with lower LH_2 delivery price, we consider the viability of the proposed boil-off capture and use systems for future prices (Fig. 5m–r). Although the U.S. Department of Energy (DOE) set future gaseous H_2 production costs target to be 1 $ per kg by 2030, current production costs of low-carbon H_2 will struggle to meet the near-term target of 3 $ per kg. The additional cost associated with transportation and liquification is nontrivial[14,15,44,45]. As such, we use a range for LH_2 purchase cost from 3 to 20 $ per kg[46].

Sensitivity and impact

The potential for cost savings is a crucial measure of economic viability, which can be calculated based on H_2 purchase price and boil-off fraction shown in *Methods*, Supplementary Note 3, and Supplementary Fig. 6. For each scenario, the cost is calculated under different perturbation of the target sensitivity variables. Figure 5a–h, 5m–p show that the boil-off capture system can bring cost savings to almost all aviation scenarios. For this market application, even when the sorbent cost increases to $20 per kg, it is still worth capturing, storing, and re-using the boil-off (Fig. 5a, b, e, f). Here, the economic benefit for improving the sorbent's H_2 uptake is not obvious. However, compared with bench-scale tests, if the uptake drops significantly (such as 80%) during actual use, the cost savings can decrease dramatically. While sensitive to the H_2 boil-off fraction, sorbent cost, and H_2 uptake across the three market applications and two end-uses (Fig. 5 and Suppl. Fig. 4), cost savings are greatest for large-scale aviation, followed by small-scale aviation, and then aerospace.

For aerospace launch applications, the current assumption of $10 per kg sorbent and experimentally-demonstrated uptakes is right on the edge of making the system economically feasible (Fig. 5i–l). However, if the sorbent can be manufactured at around $5 per kg, or 20 to 40% uptake improvement can be achieved (Fig. 5i–l), capturing, storing, and re-using the boil-off becomes economically favorable under almost all boil-off fractions. As mentioned in the *Scope, scenarios, and use-cases* section, a representative storage capacity is selected for each scenario based on reviewing the typical needs for regional and international airports, as well as aerospace launches. Sensitivity analysis on the effects of the capacities is performed and the results are shown in Supplementary Fig. 7. These results show that the economy of scale has the most significant impact on the aerospace scenarios, as they are used less frequently, and the fixed capital and refrigeration costs are distributed over fewer operation cycles. When the perturbation factor increases from 0.5× to 1.5× of the base case, the cost savings in aerospace applications increases by over $0.5 per kg H_2 for most use-cases with boil-off fraction over 10%, compared to only about less than 10% in aviation scenario. Note that for aerospace applications, the boil-off fractions are likely to be higher due to long IDLE time of the LH_2. These sensitivity results show the need for at-scale demonstrations to validate material performance beyond the experimental level, which can be done in synergy with the development and demonstration of H_2-based sustainable aviation and aerospace fuel.

From a global perspective, H_2 is expected to account for up to 20–32% of world aviation energy demand, and the future global aviation energy demand is projected to be between ~3 to 20 EJ per year for low-emission futures and business-as-usual cases, respectively[47]. The equivalent H_2 use, projected using the heating value of 120 MJ per kg and overall engine efficiency of 0.7, is 12 to 76 million metric tonnes (MMt) per year[4,48]. Assuming a conservative boil-off fraction of 5%, suggested by Airbus, and a LH_2 delivery price range of $3 to 20 per kg[46], the corresponding cost savings range from $0.11 to 0.96 for every kg of H_2 purchased (Fig. 5m–p). Using a global warming potential of 8.8 $kgCO_2e$ per kg of H_2, this suggests emissions of 5–31 MMt of CO_2e per year. For perspective, these cost savings multiplied by projected global consumption by the aviation sector, is equivalent to approximately 1 to 73 billion USD. We also note that incentives to capture boil-off will drive technology adoption, and realistic deployment scenarios are expected at higher boil-off rates and LH_2 costs.

For aerospace launches, the cost savings can range from 1 to $2.5 per kg for LH_2 delivered at $10 to $20 per kg (Fig. 5q and r). This is equivalent to over 3 million USD per dewer per year (assuming 12 fills)[34,49]. Future work is necessary to consider the demand for gaseous and re-liquefied H_2, as well as the potential for alternative use cases, such as boil-off for vehicle fleets. LH_2 boil-off poses significant environmental and safety concerns beyond cost. The indirect global warming potential of H_2 can lead to prolonged atmospheric methane, water vapor, and changed ozone levels[50]. Therefore, the environmental benefits associated with capturing, storing, and re-utilizing boil-off H_2 are significant, warranting the need for further comprehensive evaluation. As such, future work should include systematic life-cycle assessment to complement the TEA, and provide a more holistic understanding on capturing, storing, and re-using the LH_2 boil-off.

Under the assumptions of this study, several key areas that remain to be explored are the detailed reactor designs, piping and valve configurations to capture the boil-off from transfer events, and sorbent manufacturing or handling technologies—such as particle shape

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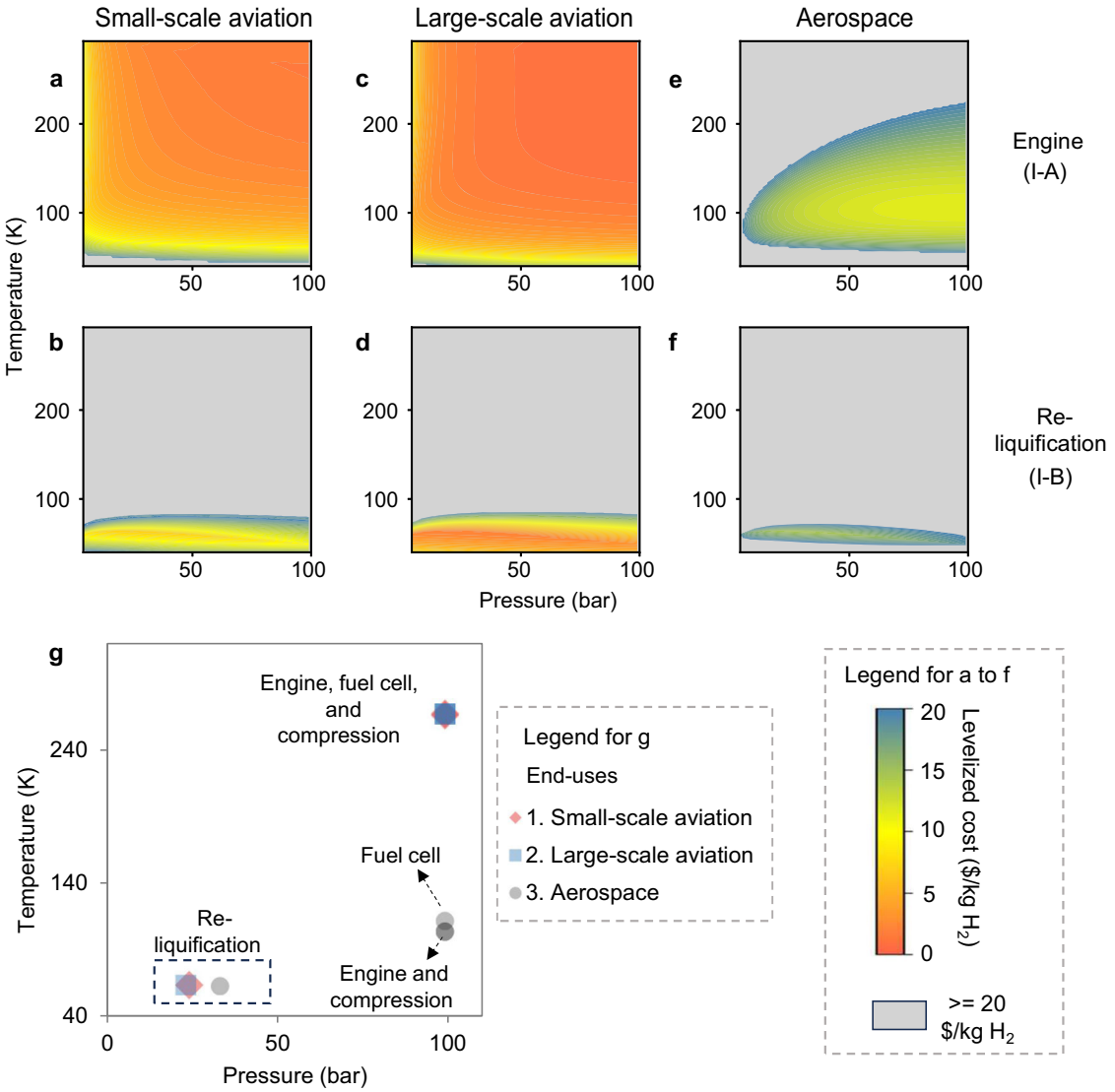

Fig. 3 | Optimum conditions for capturing, storing the boil-off for different market applications and end-uses. a–f Cost distribution of liquid hydrogen (LH_2) boil-off capture. Results are for end-use set I that includes engine and re-liquefaction. Results for set II end-uses that include fuel cells and compression are shown in Supplementary Fig. 3. **g** Optimum conditions for all end-uses and market applications. Darker color indicates overlap in optimum conditions by multiple end-uses.

and pelletizing patterns—to enable the efficient capture, storage, and release of boil-off gas, advancing the practical implementation of this technology.

Methods

Key assumptions

This section summarizes the key assumptions used in this study that are crucial to interpolating the results. Based on our literature review, we assume temperature and pressure conditions when LH_2 is first vaporized are slightly above atmospheric pressure and the boiling point of H_2, up to 4 bar and 30 K or higher, respectively, and when the boil-off reaches the capture tank, its condition is assumed to be 40 K and 3 bar[9,33,42,49]. Boil-off capture and storage conditions are set from 40 K to 298 K to align with the isotherm measurements, which will be discussed in the following section. For capture storage pressure, we set a maximum condition at 100 bar, considering it being the typical upper range of adsorption experiments and the pressure threshold of regular H_2 storage tanks[51–53]. The energy requirement to maintain the storage conditions for the captured boil-off (while being stored) is an important factor considered in this study. We assume an average value for heat of adsorption of 4 kJ per mol from measurements across the temperatures and pressures evaluated (*Methods*), and estimate net energy required to off-set the conductive heat transfer that occurs between the inside of the tank the atmospheric conditions. This is primarily guided by the temperature gradient in and out of the tank, which is set to be constant through the capture and release cycles. Our method can be used to evaluate the cost of capturing under cryogenic conditions and then stored under higher temperatures. Further, thermal management could come into play in future work, for example heat transfer between the storage system and the ambient can be leveraged to fulfill other local heating and cooling needs to benefit the cost performance.

For the use pattern of aviation applications, we assume that the system will operate on a daily basis, That is, one cycle every day for 365 days per year. For any given day, we assume primarily, the airports and flights will utilize the original LH_2, and that the system will spend 19 hours to capture and store the boil-off, and 5 h to discharge the stored boil-off[54]. For the aerospace applications, there are relatively sparse open-source data on LH_2 preparation duration and the actual usage time for each launch. Therefore, we conservatively assume that

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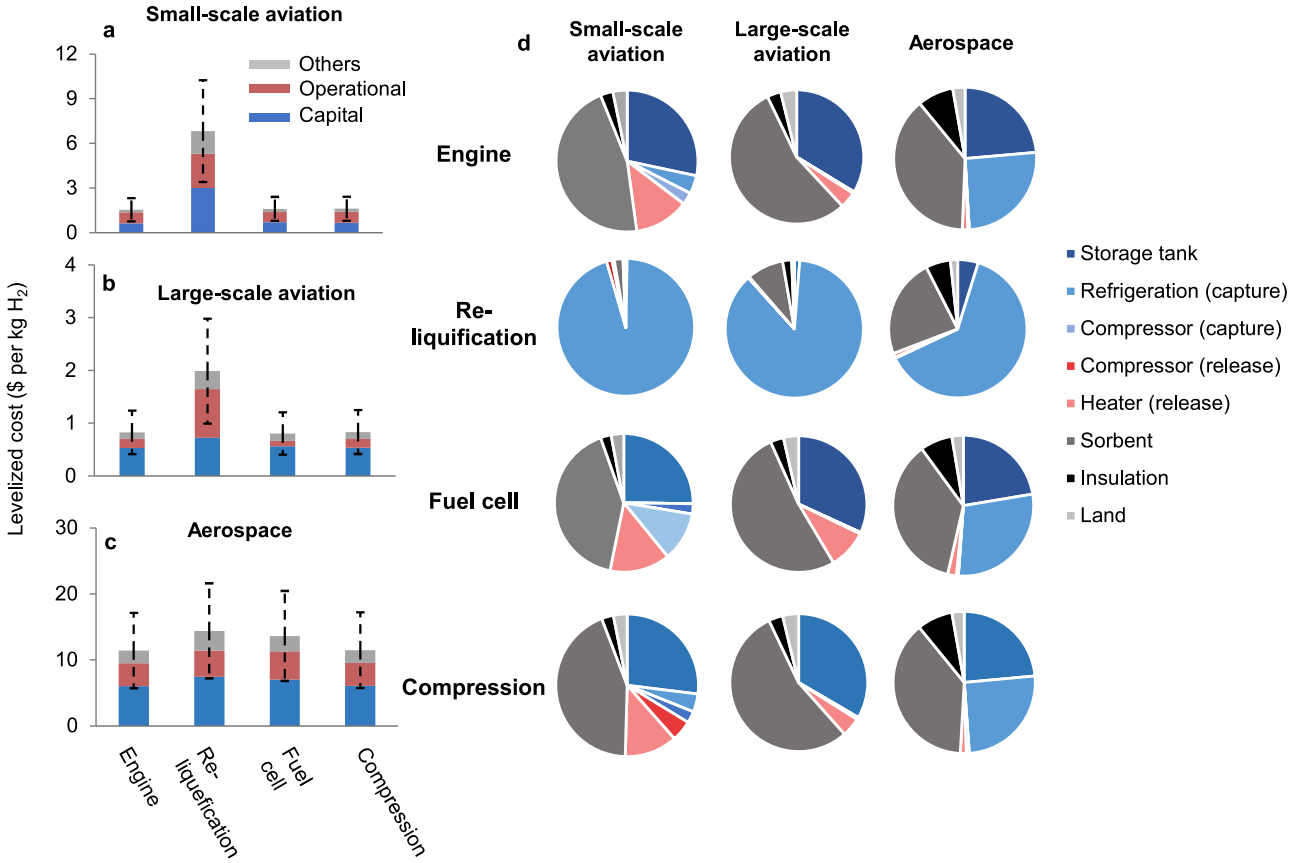

Fig. 4 | Economic performance of liquid hydrogen (LH_2) boil-off capture. **a**–**c** Levelized cost for different end-uses and market applications. Error bars represent the approximated range of uncertainties due to particle shape, bed porosity of 50% based on insights from previous analyses[25,26]. **d** cost distribution among capital components for different end-uses and scenarios.

for each cycle, the system will capture the boil-off for 240 h (e.g., IDLE, preparation, and transfer from storage tanks to launch preparation tanks), and discharge for 250 h to sustain the launch as well as other on-site testing during each cycle, summing up to around 20 days of operation in total for each cycle as the base case. Note that these time periods will affect the charge and discharge power of the coupling heater, refrigerator, and compressors, as found in our previous studies[25,26].

We assume the equipment associated with delivered LH_2 and compressed gas hydrogen is part of a lease or contract accounted for in the purchase H_2 price, which also includes auxiliary equipment such as hoses and delivery systems. For ortho-para conversion, we qualitatively evaluated its impact on energy consumption, as demonstrated in Supplementary Note 4. Our results (shown in Supplementary Fig. 8) suggest that the ortho-para conversion reactor takes 2-10% of the total cooling load during the re-liquefaction of boil-off. However, the effect of kinetics during ortho-para conversion could also impact the system performance. For example, the H_2 may not reach equilibrium under our assumed capture and release rates, and the rate of heat released or absorbed during the ortho-para conversion may present challenges. We note that it has recently been demonstrated that MOFs, a type of sorbent material class, can catalyze the conversion between ortho and para H_2[55,56], and requires further evaluation. The key assumptions and economic parameters used in this study are summarized in Suppl. Table 2.

Material performance and measurement

The representative sorbent used to evaluate the feasibility of capturing LH_2 boil off is Nuchar BAX 1500, which is a commercially available activated carbon. Its excess H_2 uptake is obtained from atmospheric conditions to cryogenic conditions (273 K to 50 K) using the setup shown in Supplementary Fig. 2.

Isotherm uptake measurements were measured on a PCT-Pro apparatus (PCT-Pro 2000), using research-grade hydrogen, up to 100 bar. Temperature control from 50 to 273 K was achieved with an ARS cryostat (DE-110 with ARS-10HW)[57]. The PCT-Pro apparatus was integrated with a cryo-cooler and a custom copper assembly to enable isothermal hydrogen capacity measurements. A key hardware modification included using temperature-controlled water circulating through copper components that are physically connected to the sample chamber assembly, so that the temperature-controlled region is expanded to include the sample support arm and the sample chamber assembly[57]. Additional water-cooled copper assemblies were added to tubing interfaces (0.125 in 316 stainless tubing) between the cryo-cooler and PCT apparatus to improve thermal stability and temperature reproducibility between empty calibrations and sample measurements. Headspace calibrations were performed with research-grade helium, with empties at each isotherm temperature measured, and at 303 K with sample present. The sorbent sample was transferred air-free after being degassed on a temperature-programmed desorption system. Excess uptake measurements were fitted to a universal dual-site Langmuir model described below using a differential evolution least-squares fitting algorithm, implemented in the REALIST package using 77, 150, and 273 K experimentally-measured isotherm data. Heats of adsorption were determined by explicitly solving the Clapeyron equation for the dual-site Langmuir equation.

Using the above methodology, the isotherm of sorbent measured in this study is shown in Fig. 2c, and fitted using dual-site Langmuir isotherms for higher temperatures (> 77 K) using Eqs. (1) and (2). For conditions at 50 K, the H_2 uptake is fitted using an analytical

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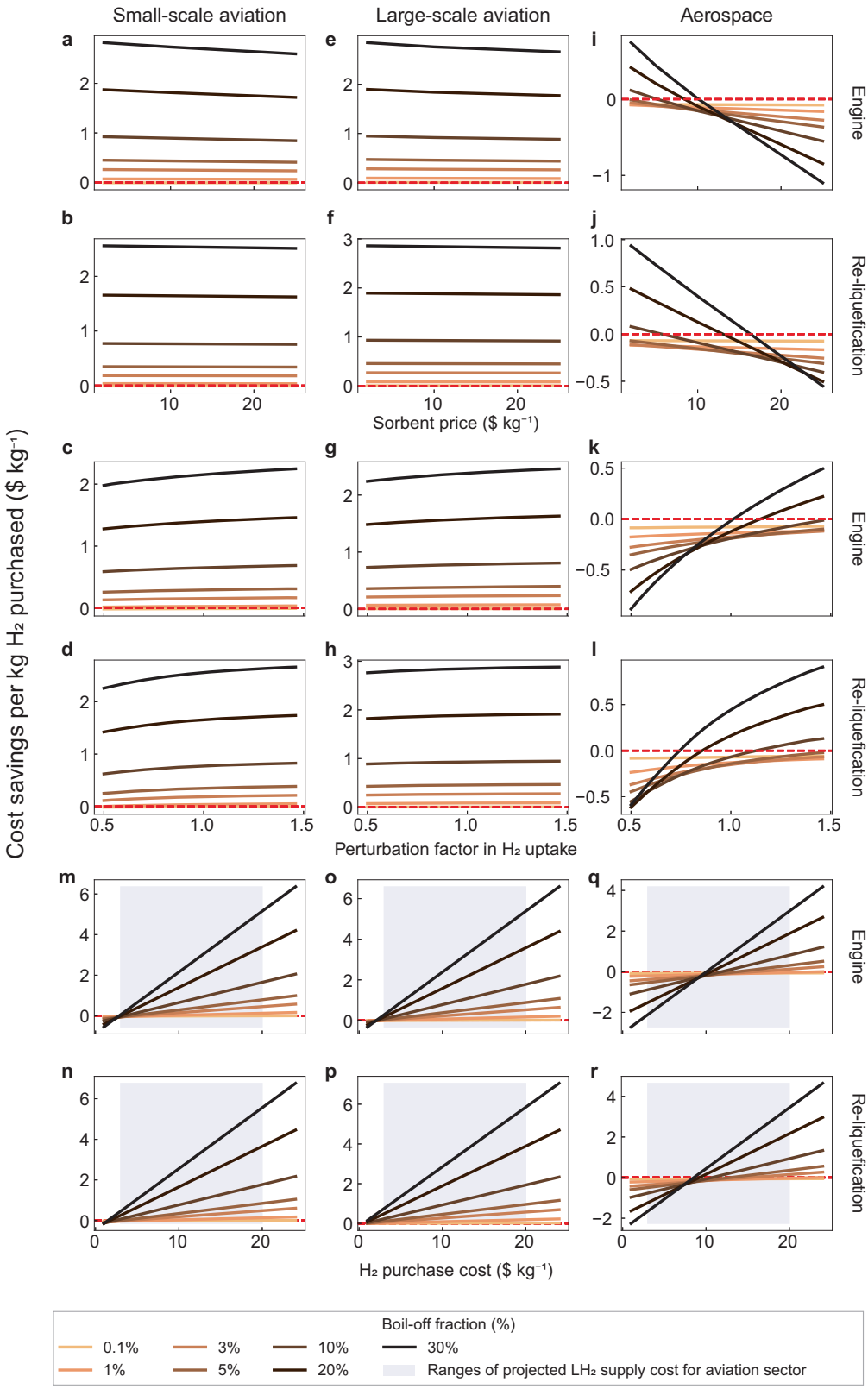

Fig. 5 | Cost savings under different liquid hydrogen (LH_2) boil-off fractions while perturbating sorbent cost and H_2 storage performance. a–d, m, n Small-scale aviation. **e–h, o, p** Large-scale aviation. **(i–l, q, r)**, aerospace. Results are for end-use set I (engine and re-liquefication). Those for end-use set II (fuel cell and compression) are included in Supplementary Fig. 4. Perturbance factor represents the ratio of the assumed H_2 uptake in sensitivity analysis vs. the H_2 uptake of the base case.

polynomial fit up to 50 bar, which is used to develop a correction factor for vapor-phase H_2 to account for inaccuracies of dual-site Langmuir model under cryogenic conditions observed during experimental measurements. The final model is summarized here in Eqs. 1 and 2[58], with additional details for the correction factors shown in Fig. 2c and Supplementary Note 2.

$$n_{excess} = \begin{cases} n_{excess\,base} = 1000 \cdot \left(n_{max} - \rho_g V_a\right)\left[\frac{(1-a)K_1 f}{1+K_1 f} + \frac{aK_2 f}{1+K_2 f}\right], & if\ T > 77 \\ correction\,factor(high) \cdot n_{excess\_base}, & if\ 50 \le T \le 77 \\ correction\,factor(low) \cdot n_{excess\_base}, & if\ T \le 50 \end{cases} \quad (1)$$

$$K_i = \frac{A_i}{\sqrt{T}} e^{E_i/(RT)} \quad (2)$$

where n_{excess} is excess H_2 uptake in the unit of mol per kg, f is fugacity (adjusted pressure for nonidealities in real gas chemical potential at specific *T, P*). *T* is the storage temperature in Kelvin. R is gas constant in kJ per mol K. The rest, $n_{\max}$, a, E_i, are fitting parameters specific to the dual-site Langmuir model.

Economic evaluation

The TEA optimization framework in this study is based on an energy balance approach, demonstrated in our previous work where H_2 was fed from 2 bar, 353 K to storage using either sorbent or metal hydride, and release back to a fuel cell at 2 bar, 353 K[25,26,59]. Besides adjusting the capture and release conditions depicted in Table 1 and *Key assumptions* Section, the different methodology used here is that compression, cooling and heating are not fixed, allowing for better coupling between storage and end-use conditions. Decisions in Eqs. (3) and (4) are applied, where the costs of compressors, heaters, and refrigerators are combined:

$$C_{P,\,thermal}(P,T) = \begin{cases} C_{P,\,comp}(P,T) + C_{P,\,ref}(P,T),\ if\ \Delta H_{net(i\to f)} < 0\ and\ P_f > P_i \\ C_{P,\,comp}(P,T) + C_{P,\,heat}(P,T),\ if\ \Delta H_{net(i\to f)} > 0\ and\ P_f > P_i \end{cases} \quad (3)$$

$$P_f \le P_i \Rightarrow C_{P,\,comp}(P,T) = 0 \quad (4)$$

where $C_{P,thermal}$ is the total capital cost for compressor ($C_{P,comp}$), refrigeration ($C_{P,ref}$), and heater ($C_{P,heat}$). Compressors are used when the pressure of the final state (P_f) is greater than the initial state (P_i), which can represent either from capture to storage, or from storage to release. The use of refrigeration or heater is based on the net enthalpy change between the initial and final states ($\Delta H_{net(i\to f)}$). The total capital cost, C_P, is calculated by Eq. (5).

$$C_P = C_{P,\,thermal}(P,T) + C_{P,\,tank}(P,T) + C_{P,\,insulation}(T) + \bar{C}_{p,\,sorbent} \cdot m_{sorbent}(P,T) + \bar{C}_{p,\,land} \cdot A_{land}(P,T) + C_{P,\,other} \quad (5)$$

where $C_{P,tank}$ is the capital cost from the storage tank determined from the analytical version of the Tankinator model[26,60]. $C_{P,insulation}$ is the insulation cost around the tank. $\bar{C}_{p,sorbent}$ is the unit cost of the sorbent in $ per kg, which is a key independent variable. $m_{sorbent}$ is the amount of sorbent needed. A_{land} is the area of land, and $\bar{C}_{p,land}$ is the unit cost of land, which we conservatively assume must be paid for at a cost of $10,000 per acre, representing industrial or rural areas[61]. In most cases, the system is housed onsite, for an area already rented or owned and only a land lease may be necessary. $C_{P,other}$ is the other non-equipment cost such as engineering and contingency. Details of our cost analysis, including how the capital costs are determined and annualized ($C_{P,annual}$), average operational costs per year ($C_{o,annual}$), and economic parameters including the capital recovery factor (*CRF*) and equipment lifetime (n_{life}), with levelized cost (LC) function summarized in Eq. (6)[25,26,59].

$$LC = \frac{C_{P,\,annual}(CRF, CEPCI, n_{life}) + C_{o,\,annual}}{mass\ of\ H_2\ released\ per\ year} \quad (6)$$

After the levelized cost is determined for each temperature and pressure, the lowest value is identified within the range of conditions modelled for each scenario. In our sensitivity analysis, the boil-off fraction and the sorbent cost and H_2 uptake are perturbed and the minimum levelized cost across temperature and pressures is determined. Finally, the cost savings in Fig. 5 is determined by subtracting the levelized cost for each parameter perturbance combination by the boil-off fraction (BF), as shown in Eq. (7).

$$Cost\ saving = (PC - LC) \cdot BF \quad (7)$$

where PC is the delivered cost in $ per kg. Detailed explanations and exemplary calculations are shown in Supplementary Note 3.

Data availability

Data supporting this study are available within the Article and Supplementary Information. Supplementary data for the high-resolution cost distribution among temperature and pressure ranges under different sensitivity scenarios used in this study are available via Figshare repository at (https://doi.org/10.6084/m9.figshare.32111647). Source data are provided with this paper.

Code availability

Supplementary codes (1- 4) associated with this manuscript, which include scripts for: finding the optimal operating conditions (Optmimal.py); sensitivity analysis for perturbance on the sorbent price (Sensitivity_cost.py) and hydrogen uptake (Sensitivity_uptake.py); illustrating use patterns for the market scenarios described in this study (Use patterns.py), are available via Figshare repository at (https://doi.org/10.6084/m9.figshare.32111647).

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Author contributions

P.P., S.S., T.G., and H.B. designed the study. P.P., C.Q., T.B. and H.B. carried out the modeling and analyses; P.P., C.Q., T.B., L.L., S.S., T.G., and H.B. investigated the assumptions for end-use scenarios. P.P. and H.B. visualized the results. P.P. and H.B. wrote the first draft. P.P., S.S., T.G., and H.B. obtained the funding. P.P., S.S., T.G., and H.B. managed the project; T.G. and H.B. supervised the project. P.P., C.Q., T.B., L.L., S.S., T.G., and H.B. contributed to editing the manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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