Hydrogen is emerging as one of the most promising energy carriers for a decarbonised global energy system. Transportation and storage of hydrogen are critical to its large-scale adoption and to these ends liquid hydrogen is being widely considered. The liquefaction and storage processes must, however, be both safe and efficient for liquid hydrogen to be viable as an energy carrier. Identifying the most promising liquefaction processes and associated transport and storage technologies is therefore crucial; these need to be considered in terms of a range of interconnected parameters ranging from energy consumption and appropriate materials usage to considerations of unique liquid-hydrogen physics (in the form of ortho–para hydrogen conversion) and boil-off gas handling. This study presents the current state of liquid hydrogen technology across the entire value chain whilst detailing both the relevant underpinning science (e.g. the quantum behaviour of hydrogen at cryogenic temperatures) and current liquefaction process routes including relevant unit operation design and efficiency. Cognisant of the challenges associated with a projected hydrogen liquefaction plant capacity scale-up from the current 32 tonnes per day to greater than 100 tonnes per day to meet projected hydrogen demand, this study also reflects on the next-generation of liquid-hydrogen technologies and the scientific research and development priorities needed to enable them.

**Broader context**

The global trade of fossil fuels amounts to over 3200 million tonnes of coal and oil and more than 850 billion cubic metres of gas each year. Average global atmospheric carbon dioxide levels have exceeded 410 parts per million and are higher than at any point in the past 800,000 years. Amidst growing pressure for countries to decarbonise their economies, future energy trading will increasingly include low- and zero-emissions production. There is a growing international consensus that hydrogen will play a key role in the world’s transition to a sustainable energy future. Transportation of hydrogen over long distances will likely require both liquefaction and intermediate storage. However, hydrogen liquefaction has not yet been deployed at a scale necessary to supply projected liquid hydrogen demand. As a fluid that is not well understood at cryogenic temperatures) and current liquefaction process routes including relevant unit operation design and efficiency. Cognisant of the challenges associated with a projected hydrogen liquefaction plant capacity scale-up from the current 32 tonnes per day to greater than 100 tonnes per day to meet projected hydrogen demand, this study also reflects on the next-generation of liquid-hydrogen technologies and the scientific research and development priorities needed to enable them.

**1 Introduction**

There is increasing consensus that hydrogen will be essential for a global transition to a sustainable energy economy. This transition is becoming increasingly important in light of both ambitious international climate goals and record-breaking carbon dioxide levels realised in 2019.1–5 Hydrogen can both enable the decarbonisation of sectors that are energy-intensive, including long-haul transport, industrial chemicals, and mineral processing,6–8 and be paired with renewables to store energy and overcome the challenges of intermittency.5 It can also be used as an energy carrier to export renewable energy from regions of abundant renewable resources to nations with limited energy resources.2
Such a transition will, however, require the development of hydrogen value chains that are both sustainable and substantial in scale. Consequently, hydrogen road maps have been outlined for regions and countries such as the United States,\textsuperscript{10} European Union,\textsuperscript{11,12} Japan,\textsuperscript{13,14} Australia,\textsuperscript{15} Germany\textsuperscript{16} and the United Kingdom.\textsuperscript{17} Fig. 1 shows a block diagram representing the hydrogen value chain comprising four primary stages, labelled here as (1) resources, (2) production, (3) storage & transport, and (4) utilisation. Each of these stages can be realised using one of multiple possible options resulting, therefore, in a relatively large number of pathways by which the complete hydrogen value chain can be traversed. In addition to technical merit and cost, the selection of an option within a given stage of the value chain is influenced by both previous and subsequent stages. These inter-stage interactions mean that the hydrogen value chain can be considerably more complicated than other comparable energy value chains.\textsuperscript{18–20}

Primary energy sources are either carbon-based (natural gas, coal, biomass) or non-carbon based (wind, solar, nuclear). Water is another resource that can be critical to the first stage of the hydrogen value chain, particularly if the primary energy is produced in electrical form. These resources are then converted into hydrogen-containing materials through a variety of processes\textsuperscript{21–56} during the production stage. Production of \( \text{H}_2 \) today is dominated by the use of fossil fuels\textsuperscript{57} because this is the cheapest way of producing, for example, the fertiliser needed for food production. However, this does not account for the latent cost associated with the substantial emissions of \( \text{CO}_2 \) resulting from such \( \text{H}_2 \) production.

Table 1 presents comparative data for the current costs of producing \( \text{H}_2 \) with low or no \( \text{CO}_2 \) emissions. Pairing hydrogen produced from fossil fuels with carbon capture and storage (CCS)\textsuperscript{5} (to produce so-called blue hydrogen) can increase the associated cost by up to 54\% while reducing \( \text{CO}_2 \) emissions.\textsuperscript{37} However, the scale of CCS\textsuperscript{†} needed for blue \( \text{H}_2 \) production technologies could represent a significant constraint on the role it can play within decarbonised energy supply chains. Green hydrogen production technologies\textsuperscript{38–56} (from renewable energy sources together with electrolysis, solar thermochemical splitting and biochemical processes) also face significant challenges as they are still limited in scale,\textsuperscript{‡} and their energy consumption is not yet cost-competitive. Nevertheless, the improving efficiencies and cost-reductions occurring in renewable energy generation and green hydrogen production suggest a cost curve trajectory that may bring them into line with blue hydrogen in the coming decade.\textsuperscript{59}

Storage and Transport is crucial to the establishment of a hydrogen value chain. The focus of this review, liquid hydrogen, is one of many technologies\textsuperscript{63–82} likely to play a significant role in the hydrogen value chain and its relation to the focus of this review into hydrogen liquefaction.

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\( \text{†} \) Global capture and storage capacity of projects currently operating or under construction is around 40 million tonnes per annum (Mtpa).

\( \text{‡} \) The largest PEM electrolyser currently in use has a capacity of 20 MW. This is equivalent to a hydrogen production capacity of 8 TPD, assuming a power consumption of 66 kWh kg\textsubscript{H}_2\textsuperscript{–1}.
the international trade of hydrogen. While the production stage usually generates gaseous H₂, storing and transporting the associated energy over long time scales and distances requires the implementation of a physical or chemical conversion process within the 3rd stage of the value chain to achieve a viable energy density. The choice of which hydrogen vector to select to this end is strongly coupled to the mode of transport best-suited, both technically and from a cost perspective, to the intended end-use of the hydrogen with distance and the infrastructure available at both ends of the supply-chain being additional considerations.§

The final stage of the hydrogen value chain is utilisation, which is currently dominated by chemical feedstock83 (e.g. fertilisers, oil-refining, plastics, semi-conductors) and aerospace applications (rocket fuel).84–96 However, while global hydrogen production is now approximately 75 million tonnes per year,97 annual global demand is projected to reach 621 million tonnes, with the majority being used in the transportation sector.98 Certain hydrogen vectors are chemically incompatible with particular utilisation options, and thus the cost of converting them back to a compatible form must be factored in to any analysis used for vector selection. The very-high purity requirements of H₂ fuel cell vehicles are similar to those needed and achieved during the hydrogen liquefaction process. For this reason, liquid hydrogen is expected to play a significant role within the supply chains needed to meet projected global demand.

### Liquid hydrogen's role in the value chain

While liquid hydrogen's strengths as a vector include purity, end-use versatility, and ease of gasification, it also suffers from disadvantages relative to other possible vectors. Table 2 presents a summary of key properties of the primary hydrogen vectors available for storage and transport. These properties, together with an analysis of the costs associated with each stage of the liquid hydrogen supply chain, help with assessments of (i) applications for which it is most suited relative to other possible vectors, and (ii) technology gaps that need to be addressed to improve economic viability.

An additional advantage of liquid hydrogen over other possible vectors include its relatively high volumetric hydrogen density (80% greater than gaseous H₂ compressed to 70 MPa, and 50% greater than methylycyclohexane). The energy costs of producing ammonia and methanol per unit mass of hydrogen are comparable with liquid hydrogen yet the latter has no energy cost associated with dehydrogenation, which is required for fuel cell applications. For direct combustion, dealing with the greenhouse gases and other pollutants that can be emitted by liquid vectors (CO₂ for methanol, NO₂ and N₂O for ammonia) can also be a significant issue.

Nevertheless, liquid hydrogen is characterised by several appreciable limitations and challenges that restrict its current use. These include:

- **Economics**: hydrogen liquefaction is an energy-intensive process. Current processes have specific energy consumptions (SEC) of between (11.9 and 15) kWh kg⁻¹ H₂, which is (35 to 45%) of the lower heating value of hydrogen.¹²⁴⁻¹²⁶ This contributes significantly to the current specific liquefaction cost (SLC) range of (2.5–3.0) US$/kgLH₂.¹²⁴⁻¹²⁷

- **Cryogenic loss**: boil-off loss associated with the storage, transportation and handling of liquid hydrogen can consume up to 40% of its available combustion energy.¹³¹ For example, the NASA Space Shuttle program carried out from 1977 to 2011 purchased over 24 500 tonnes of liquid hydrogen, of which

### Table 1  Summary of low carbon or carbon neutral hydrogen production processes. All data sourced are from base case scenarios. Efficiencies are expected to increase with time

<table>
<thead>
<tr>
<th>Production process</th>
<th>Ref.</th>
<th>Feedstock</th>
<th>Power req. [kWh kg⁻¹ H₂]</th>
<th>H₂ capacity [TPD]</th>
<th>Capex [MS]</th>
<th>Opex a [MS per year⁻¹]</th>
<th>Cost b [US$ per kgLH₂]</th>
<th>Capacity factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMR with CCS</td>
<td>25, 37, 60 and 61</td>
<td>Natural gas</td>
<td>44–50</td>
<td>210–341</td>
<td>226–463</td>
<td>16.1</td>
<td>1.63–1.99</td>
<td>90–95%</td>
</tr>
<tr>
<td>CG with CCS</td>
<td>37, 61 and 62</td>
<td>Coal</td>
<td>47.2</td>
<td>277–500</td>
<td>546–677</td>
<td>27.6</td>
<td>1.63–2.26</td>
<td>85%</td>
</tr>
<tr>
<td>Wind-Electrolysis</td>
<td>48 and 49</td>
<td>Water</td>
<td>44.7–53.4</td>
<td>10</td>
<td>150–500</td>
<td>9.13–25.3</td>
<td>2.37–5.69</td>
<td>41–55%</td>
</tr>
</tbody>
</table>

* a Variable costs excluded. b Capacity factor of the hydrogen production method. Capacity factor is the unitless ratio of an actual electrical energy output over a given period of time to the maximum possible electrical energy output over that period. For Solar PV and Wind electrolysis, the operation of the electrolyser is dependent on the renewable energy source and as such, the system has a similar capacity factor. For SMR and CG with CCS, the capacity factor is affected by maintenance requirements. c Feedstock cost ranges from: 5.76–10.5 US$/GJ. d Feedstock cost: 1.15–2.16 US$/GJ. e Studies were conducted 5 years apart, 2015 and 2020. Variance in costs and capacity factor are attributed to significant developments within the solar photovoltaic industry made during that time. f Renewable energy with feedstock cost included in plant capital. g Shaner et al. estimates yearly Opex for electrolyser to be 3.2% of the Capex. Neither study states other Opex values. h Assuming the electrolyser is off-grid and powered solely by the renewable energy source. This value is location dependent. If connecting to the grid is possible, the electrolysers may operate at their maximum capacity, increasing the capacity factor to 97%. However, as most grids are currently fossil-fuel derived, CO₂ emissions would be emitted. i Data retrieved from conceptual study investigating near, mid and long-term production costs associated with a 50 tonnes per day (TPD) standalone wind-hydrogen system. Stated costs is the range between the near and long-term scenarios for when the system is not connected to the grid.
54.6% was used on-board; the rest was lost during storage, loading, or replenishment.

- Safety: liquid hydrogen is not a common global shipping commodity. The lack of safety standards and regulation around hydrogen-based processes (especially at large-scale) could impede the establishment of liquid hydrogen supply chains.\(^{125}\)

- Scale: currently, the largest single liquefier has a capacity of 32 tonnes per day (TPD), and the total global capacity is 350 tonnes per day. By 2050, the Hydrogen Council has estimated that 10% of total hydrogen demand, or 0.17 million tonnes per day, could be transported by sea.\(^{125}\) To ship even a modest fraction of this amount as liquid will require a substantial scale-up of liquefaction capacity. Achieving this goal will likely help mitigate the challenges of energy cost and economics.\(^{25}\) However, the technical challenges of scaling-up the necessary equipment (compressors, turbines and coldboxes) items are significant.

This review details the current state of knowledge, technology, and industrial practice relevant to the liquid hydrogen supply chain. Its objectives are to (i) provide an overview of the main challenges associated with producing and storing liquid hydrogen, and (ii) identify the primary opportunities for improving upon the four limitations detailed above: economics, cryogenic loss, safety and scale. To achieve these objectives the review starts by detailing the properties of molecular hydrogen that are relevant to liquefaction (Section 2), with a focus on the role that the spin isomers ortho- and para-hydrogen have on the thermodynamics and kinetics of liquefaction. Strengths and deficiencies in the models available for engineering design are identified together with knowledge and data gaps that if addressed would likely lead to process improvements. In Section 3, current approaches to hydrogen liquefaction are summarised before conceptual designs expected to deliver the needed efficiency improvements are reviewed. The storage and transport of liquid hydrogen is covered in Section 4, with a focus on the prediction and minimisation of boil-off losses. The specific challenges associated with safety and scale-up of the liquid hydrogen supply chain are considered in Section 5. Finally, a summative list of research and development priorities is presented.

### 2 Fundamental properties of molecular hydrogen

#### 2.1 Mixture of ortho- & para-hydrogen

Molecular hydrogen occurs in two isomeric forms, ortho-hydrogen and para-hydrogen, differentiated by the nuclear spin

<table>
<thead>
<tr>
<th>Vector properties</th>
<th>CGH₂</th>
<th>CGH₃</th>
<th>LH₂</th>
<th>NH₃</th>
<th>MeOH</th>
<th>LOHC</th>
<th>LNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric density(^{a})</td>
<td>p/MPa</td>
<td>35</td>
<td>70</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Gravimetric hydrogen content</td>
<td>kJ/kg</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>57.4–90.4</td>
<td>1.67–4.4</td>
<td>1.67–4.4</td>
</tr>
<tr>
<td>Volumetric H₂ density</td>
<td>kWh/kg carrier (^{a})</td>
<td>33.3</td>
<td>33.3</td>
<td>33.3</td>
<td>5.93</td>
<td>4.04</td>
<td>4.04</td>
</tr>
<tr>
<td>Specific energy [mass](^{j})</td>
<td>kWh/L carrier</td>
<td>1.67–4.4</td>
<td>4.7</td>
<td>6–15 (^{d})</td>
<td>2–4.17 (^{i})</td>
<td>0.03–0.21 (^{e})</td>
<td></td>
</tr>
<tr>
<td>Specific energy [volume](^{f})</td>
<td>kWh/kg H₂ carrier (^{l})</td>
<td>7.94</td>
<td>6–15</td>
<td>11.2–22.5</td>
<td>0.967</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Energy to produce carrier</td>
<td>kWh/kg H₂ carrier (^{l})</td>
<td>7.94</td>
<td>6–15</td>
<td>11.2–22.5</td>
<td>0.967</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Energy for dehydrogenation</td>
<td>kWh/MeOH</td>
<td>5–13.2</td>
<td>20</td>
<td>18.2–45.5</td>
<td>57.4–90.4</td>
<td>1.67–4.4</td>
<td>1.67–4.4</td>
</tr>
<tr>
<td>End product consumed(^{d})</td>
<td>[wt%]</td>
<td>2.2–4.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCOP (^{i})</td>
<td>[US per kg]</td>
<td>0.22–0.28 (^{m})</td>
<td>2.83 (^{m})</td>
<td>0.5–3 (^{m})</td>
<td>1–1.7 (^{m})</td>
<td>2–4.17 (^{i})</td>
<td>0.58–1.56 (^{e})</td>
</tr>
</tbody>
</table>

\(^{a}\) CGH₂ – compressed hydrogen gas, LH₂ – liquid hydrogen, NH₃ – ammonia, MeOH – methanol, LOHC – methylcyclohexane. \(^{b}\) Volumetric density is obtained using reference thermodynamic models implemented in REFPROP 10. \(^{1}\) Excluding LNG, specific energy refers to amount of hydrogen available, in kwh equivalent terms, within one unit of carrier. LHv of hydrogen used: 120 MJ kg \(^{-1}\) \(^{f}\) and LHv of LNG [methylene]: 50 MJ kg \(^{-1}\) \(^{f}\) to calculate values. Molecular mass taken from the National Centre for Biotechnology Information. \(^{4}\) Includes current industrial hydrogen liquefaction plant technology and conceptual studies for a range of plant capacities, from 5 TPD to 50 TPD. The specific energy consumption of liquefiers operated in the USA is stated to range between 12.5 and 15 kWh kg \(^{-1}\) \(^{f}\) for capacities between 5.4 and 32 TPD. \(^{4}\) Value calculated from the energy requirements for ammonia synthesis only. \(^{j}\) Electricity consumption to synthesise methanol from CO₂. This value includes energy requirement for water electrolysis to produce hydrogen. The study evaluates 2 different scenarios, transporting CO₂ and placing the CO₂ recovery facility nearby to the electrolyser. \(^{f}\) Required energy to hydrogenate toluene. \(^{4}\) Based on the energy efficiencies of various natural gas liquefaction cycles. \(^{5}\) Includes catalytic steam reforming of methanol. \(^{6}\) kWh kg \(^{-1}\) \(^{f}\) and methanol electrolysis: 15.4–12.4 kWh kg \(^{-1}\) \(^{f}\). The methanol electrolysis study referenced contains experimental data. Energy consumption is expected to decrease as the technology develops, hence the best case is stated. \(^{j}\) Range varies due to the difference in enthalpies of dehydrogenated listed in the studies. \(^{d}\} Percentage of end product consumed, either hydrogen or LNG. Calculated by total required energy to produce carrier [kWh kg \(^{-1}\) \(^{l}\)] over the specific energy of the end product. Hydrogen specific energy: 33.3 kWh kg \(^{-1}\) \(^{l}\), LNG specific energy: 15.3 kWh kg \(^{-1}\) \(^{l}\). \(^{4}\} LCOP – levelized cost of end product. Does not include hydrogen feed costs or transportation. \(^{8}\} Includes Capex, Opex for compression and storage. Modelling assumes storage capacity is charged and discharged on a daily basis from tanks of 100 m \(^{3}\) capacity. Stated cost includes the cost associated with hydrogenation and dehydrogenation. \(^{b}\} Includes current industrial hydrogen liquefaction plant technology and conceptual studies for a range of plant capacities, from 5 TPD to 50 TPD. The specific energy consumption of liquefiers operated in the USA is stated to range between 12.5 and 15 kWh kg \(^{-1}\) \(^{f}\) for capacities between 5.4 and 32 TPD. \(^{4}\} Value calculated from the energy requirements for ammonia synthesis only. \(^{j}\) Electricity consumption to synthesise methanol from CO₂. This value includes energy requirement for water electrolysis to produce hydrogen. 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Small scale – 350 TPD [MeOH], large scale > 1000 TPD [MeOH]. \(^{4}\} Includes LOHC production, hydrogenation and dehydrogenation costs. \(^{5}\} Study quantitatively assessed various natural gas liquefaction processes. Costs include production, maintenance and amortized capital costs, excludes feed natural gas costs. The converted was from $ per GJ to $ per kg using the LHV of LNG [methylene, 50 MJ kg \(^{-1}\) \(^{1}\)].
state of the protons in each hydrogen atom. Fig. 2 shows a schematic representation of these two nuclear spin isomers, together with a curve showing the fraction of para-hydrogen in an ensemble of H₂ molecules at equilibrium as a function of temperature. For a given temperature, the equilibrium ratio of ortho- to para-hydrogen concentrations (\( c_{\text{OH}_2} \) and \( c_{\text{pH}_2} \), respectively) is given by: \[ K_{\text{OP}} = \frac{c_{\text{OH}_2}^{\text{eq}}}{c_{\text{pH}_2}^{\text{eq}}} = \frac{3 \times \sum_{L=1,3,5} (2L + 1) \cdot \exp \left( \frac{-F}{kT} \right)}{\sum_{L=0,2,4} (2L + 1) \cdot \exp \left( \frac{-F}{kT} \right)} \] (1)

Here \( L \) is the molecule’s rotational quantum number, with even values associated with para-hydrogen and odd values with ortho-hydrogen; \( k \) is the Boltzmann constant, \( T \) is the hydrogen temperature and \( F \) is the energy of the rotational state, which is given by eqn (2): \[ F = B_0 L(L + 1) - D_0 L^2(L + 1)^2 + H_0 L^3(L + 1)^3 \] (2)

where \( B_0 = 7.36 \text{ meV} \) is the rotational constant of hydrogen, and \( D_0 = 5.69 \times 10^{-3} \text{ meV} \) and \( H_0 = 6.45 \times 10^{-8} \text{ meV} \) are the rotational energy distortion constants.

With decreasing temperature, the probability of a molecule being in a para-hydrogen state increases because of its lower energy, and consequently the equilibrium ortho–para ratio approaches zero. Intermolecular forces between two ortho-hydrogen molecules are slightly stronger than those between two para-hydrogen molecules because of the former’s larger total nuclear spin. The ortho-para ratio thus affects the magnetic, optical, volumetric and thermal properties of the hydrogen.\(^{131}\)

Accordingly, thermodynamic descriptions of hydrogen’s properties at equilibrium should ideally represent the substance as a mixture with a temperature dependent composition. However at temperatures where a liquid phase can exist (<33 K), the substance may be well-approximated as pure para-hydrogen, while at ambient temperatures and above a pseudo-pure substance known as normal hydrogen consisting of 75% ortho-hydrogen and 25% para-hydrogen provides an excellent representation of the fluid.

When normal hydrogen is cooled appreciably, care must be taken with both the modelling approach and any physical handling of the substance. Quantum mechanical selection rules related to the conservation of molecular angular momentum mean that the transition from ortho- to para-hydrogen is forbidden and cannot occur spontaneously without an external interaction, such as a molecular collision in the presence of an inhomogeneous magnetic field as discussed below. In the absence of a suitable catalyst to facilitate the conversion, if normal hydrogen is rapidly cooled from ambient to cryogenic temperatures the time required before the equilibrium composition is reached can be of the order of days or weeks. Moreover, the conversion from normal to para-hydrogen is exothermic, releasing 525 kJ kg\(^{-1}\) of heat, which is larger than the enthalpy of vaporisation at liquid hydrogen’s normal boiling point (448 kJ kg\(^{-1}\)).\(^{111–113}\)

Thus, the effective and efficient conversion of ortho- to para-hydrogen is extremely important to industrial-scale applications of hydrogen liquefaction and storage. If insufficient time is allowed for the kinetics of the ortho–para conversion reaction to occur, normal hydrogen that is liquefied too rapidly will generate excessive amounts of boil-off gas. Excessive amounts of boil-off gas may cause over-pressurisation of the cryogenic storage tank, leading to serious safety issues. Even if the pressure build up is not rapid, the slow transformation of ortho- to para-hydrogen is one of the barriers to long-term liquid hydrogen storage given that the heat of conversion can evaporate more than 70% of the stored liquid hydrogen.\(^{133}\)

Consequently, so-called catalyst materials are integrated into the construction of industrial hydrogen liquefaction processes. In the presence of such catalysts the kinetics are approximately first order with full conversion achieved in minutes.\(^{134–136}\) The principle cost to their use is an increased pressure drop across the liquefier.

### 2.2 Thermodynamic property descriptions for hydrogen liquefaction

**Thermodynamic models for pure hydrogen.** The liquefaction of a fluid requires an adequate knowledge of its thermodynamic properties, starting with its critical point. The slow rate at which ortho-hydrogen converts to para-hydrogen in the absence of a catalyst means it is possible to determine experimentally a critical point for both normal hydrogen\(^{69,137,138}\) and para-hydrogen.\(^{139,140}\) Table 3 lists the critical point conditions for para-, ortho- and normal hydrogen determined by Leachman et al.\(^{141}\)

<table>
<thead>
<tr>
<th>( p )-H₂</th>
<th>( c )-H₂</th>
<th>( n )-H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_c/K )</td>
<td>( p_c/\text{MPa} )</td>
<td>( \rho_c/\text{kmol m}^{-3} )</td>
</tr>
<tr>
<td>32.938</td>
<td>1.2858</td>
<td>15.538</td>
</tr>
<tr>
<td>33.22</td>
<td>1.31065</td>
<td>15.445</td>
</tr>
<tr>
<td>33.145</td>
<td>1.2964</td>
<td>15.508</td>
</tr>
</tbody>
</table>

Table 3 Critical properties of para-, ortho- and normal hydrogen.

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Leachman et al. developed a reference equation of state (EOS) for para-, ortho- and normal hydrogen, valid from the triple point temperature of each fluid (≈ 14 K) to 1000 K at pressures to 2000 MPa. Within this EOS, the reduced Helmholtz energy of each fluid is represented by a function that contains approximately 30 terms that are either polynomial, exponential, Gaussian or logarithmic functions of the reduced density and inverse reduced temperature. Each of the 30 terms has between one and seven adjustable parameters that were determined via non-linear least squares regression to the primary experimental data sets.

With this degree of flexibility, the Leachman EOS for para-hydrogen has an estimated expanded uncertainty (95% confidence interval) of 0.1% in density at temperatures up to 250 K and pressures to 40 MPa. Calculated heat capacities, speeds-of-sound and vapour pressures for para-hydrogen have estimated uncertainties of 1%, 0.5% and 0.1%, respectively at pressures below 100 MPa. The reference EOS for normal hydrogen has a similar performance over the same ranges and conditions: in the range (250 to 450) K at pressures up to 300 MPa, densities have an estimated uncertainty of 0.04%.

These small uncertainties make the reference EOS of Leachman et al. more than sufficient for the purpose of designing and optimising hydrogen liquefaction processes, assuming that the ortho–para ratio is known or controlled adequately at each point. Several low-cost or free software packages, including REFPROP 10,89 TRENDS 4142 and ThermoFAST Web,143 contain implementations of the reference EOS enabling calculations of the enthalpy changes, volumes and vapour–liquid equilibrium conditions needed to size and evaluate the performance of various liquefaction cycles. However, most commercial process simulation software packages do not typically use reference EOS, at least by default, because (i) their high-degree of non-linearity can make the solution of mass and energy balance equations impractically slow; (ii) there is often a need to also consider mixtures at some (early) stage within the process simulation; and (iii) hydrogen is often treated as a pure fluid (normal) with no consideration of the temperature-dependent ortho–para ratio. Consequently, commercial process simulation software packages tend to utilise cubic equations of state, such as the Peng–Robinson EOS,144 to represent pure hydrogen. Cubic EOS typically utilise three fluid-specific parameters based on the substance’s critical point and normal boiling point. They then rely on a corresponding-states approach145,146 to calculate thermodynamic properties for the pure fluid and its mixtures over a wide-range of conditions. However, as discussed by Rowland et al.,147 the corresponding states approach tends to fail for fluids whose critical properties are influenced by quantum phenomena such as hydrogen, helium and neon.148,149

When the intermolecular separation is similar to the molecule’s de Broglie wavelength, λ\text{th}, quantum effects can influence the fluid’s properties significantly: for liquid hydrogen at its normal boiling point, H\textsubscript{2} has a de Broglie wavelength around 0.27 nm and an intermolecular separation of 0.66 nm. Thus the liquefaction of hydrogen provides a rare example of quantum mechanics impacting an industrial process in two separate ways: conversion between the ortho- and para- quantum states, and the wave-like properties of H\textsubscript{2} molecules at low temperatures.

It is possible to correct the Peng–Robinson model of H\textsubscript{2} for the effects of its de Broglie wavelength by modifying the intermolecular pair potential using the method of Feynman and Hibbs.150 Essentially, the correction makes the co-volume (size) parameter b in the cubic EOS temperature dependent, which in turn leads to a more robust mathematical representation of the pure fluid’s vapour pressure curve. Aasen et al.151 applied this method to develop accurate quantum-corrected cubic equations of state for hydrogen, helium, neon, deuterium and their mixtures. With no new fitting parameters, significant improvements were achieved in the ability of the cubic equation to represent density, heat capacities and enthalpy changes at saturation for normal hydrogen (no consideration is given to ortho–para conversion). Perhaps even more significantly, given that the primary utility of cubic models is the description of vapour–liquid equilibrium (VLE) in mixtures, was the ability of the quantum-corrected Peng–Robinson EOS to represent the experimental VLE data for helium-neon and hydrogen-helium. This could be an important tool in the development and simulation of next-generation liquefaction processes that achieve higher efficiencies through the use of “quantum refrigerant mixtures” with varying ratios of (He + Ne + H\textsubscript{2}).

Mixtures with hydrogen and refrigerants. There are two general reasons for fluid mixture property predictions in the design of hydrogen liquefaction processes:

The first reason relates to the pre-treatment processes where impurities must be separated from the hydrogen prior to liquefaction to avoid solids forming in the cryogenic heat exchangers. The nature of the likely impurities depends upon the source of the hydrogen: if it is produced by SMR, then CH\textsubscript{4}, H\textsubscript{2}O, CO and CO\textsubscript{2} should be considered, while if it is produced by electrolysis then H\textsubscript{2}O, O\textsubscript{2}, N\textsubscript{2} and Ar might need to be removed before or during liquefaction. The state-of-the-art for describing the thermodynamic properties of such mixtures is the GERG-2008 EOS,152 which provides a framework for calculating the Helmholtz energy of mixtures containing up to 21 components, including normal H\textsubscript{2} and the seven impurities listed above. However, the GERG-2008 EOS was developed for natural gas mixtures, with the primary focus being CH\textsubscript{4} dominant systems with H\textsubscript{2} considered only as an impurity. Furthermore the priority of the original GERG-2008 EOS was accurate calculations at pipeline conditions, with less weighting given to cryogenic temperatures (leading to the development of EOS-LNG153 in 2019).

To help address the resulting deficiencies of property calculations for multi-component hydrogen dominant mixtures, Beckmüller et al.154 have developed new Helmholtz EOS for binary mixtures of H\textsubscript{2} + CH\textsubscript{4}, H\textsubscript{2} + N\textsubscript{2}, H\textsubscript{2} + CO\textsubscript{2} and H\textsubscript{2} + CO that can be used within the GERG-2008 framework. They replaced the pure-fluid model for H\textsubscript{2} used in the original GERG-2008 model with the reference EOS of Leachman et al. for normal hydrogen, and also developed a new binary-specific departure functions to represent the available mixture data. The most significant of the improvements resulting from the new models
of Beckmüller et al. is the accurate representation of the available low temperature VLE data, particularly for \( \text{H}_2 + \text{CO}_2 \) at \( T \leq 296 \text{ K} \), \( \text{H}_2 + \text{CH}_4 \) at \( T \leq 140 \text{ K} \), \( \text{H}_2 + \text{N}_2 \) at \( T \leq 110 \text{ K} \), and \( \text{H}_2 + \text{CO} \) at \( T \leq 95 \text{ K} \); for these systems phase boundary predictions around or above 10 MPa made using the original GERG-2008 EOS are in substantial error. While only normal hydrogen is considered, the new Helmholtz models are valid over the same ranges of temperature and pressure as the original GERG-2008 (60 K \( \leq T \leq 700 \text{ K} \), \( p \leq 70 \text{ MPa} \)).

The second reason that fluid mixture property predictions are needed for hydrogen liquefaction process design is the selection and optimisation of mixed refrigerants (MRs). Conceptual studies have found that using MRs containing between two and five components can significantly improve the liquefaction cycle efficiency as detailed below. Common MR compositions can include hydrogen, nitrogen, neon, helium, and hydrocarbons ranging from methane to butane.\(^{155}\) The aforementioned quantum-corrected cubic EOS by Aasen et al.\(^{151}\) are one option for use in liquefaction simulations; these should provide reasonably accurate estimates of the cryogenic refrigerant mixture VLE properties. However, the changes in refrigerant enthalpies central to liquefaction cycle design are not so well represented by cubic EOS. Multi-parameter mixture Helmholtz energy models are the most accurate option for such calculations and should be used where available. Tkaczuk et al.\(^{156}\) have reported accurate Helmholtz energy EOS models with binary-specific functions for helium and neon, helium and argon and neon and neon and argon mixtures. For refrigerant mixtures that include hydrogen with the noble gases, an extension of the work by Beckmüller et al. is underway; however, this approach will be limited by the use of normal rather than equilibrium hydrogen within the GERG-2008 framework. While this may not be problematic for predictions of phase equilibria and density it is an issue for calculations of the caloric properties needed for energy balances.

### 2.3 Transport properties and experimental data needs

The thermodynamic models for hydrogen are roughly one order of magnitude less accurate than those available for other fluids like methane or nitrogen, primarily because of the significantly more limited experimental data.\(^{157}\) Jacobsen et al.\(^{158}\) reviewed the experimental thermodynamic data available for normal and para-hydrogen and suggested a range of priority measurements needed to advance hydrogen property predictions at conditions of industrial interest. To improve the simulation of liquefaction processes, Jacobsen et al.\(^{158}\) recommended new measurements of density, speed of sound and heat capacity for normal hydrogen in the gaseous and liquid phases be acquired at temperatures below 50 K, while such measurements for para-hydrogen be conducted above 100 K because this would help resolve the contributions due to ortho-hydrogen. To acquire data with sufficiently low uncertainty, state-of-the-art experimental techniques for thermodynamic property measurements should be utilised, together with the ability to monitor the ortho–para ratio as a function of time (e.g. using Raman spectroscopy).\(^{159}\)

For hydrogen-rich mixtures, new data are required to improve upon and extend the approach of Beckmüller et al.\(^{153}\) For the four binaries they considered, the greatest data need identified was single-phase density data, especially for the normal \( \text{H}_2 + \text{CO} \) system. However, particularly for the temperature range (30 to 150) K, (ternary) mixture measurements of equilibrium hydrogen with various other compounds likely to be present as either impurities in hydrogen production or components in mixed refrigerants should be prioritised. For mixed refrigerant candidates, enthalpy, heat capacity and/or speed of sound data should be acquired in addition to vapour–liquid equilibrium measurements, while for likely impurity compounds, the focus should be on solubility measurements as a function of temperature and concentration.

Both the experimental data situation and, consequently, the accuracy of predictive models are worse for the transport properties of hydrogen and its mixtures. Models for the viscosity and thermal conductivity of hydrogen are needed to estimate, respectively, pressure drops and heat transfer coefficients in various unit operations within the liquefaction process (e.g. cryogenic heat exchangers). Advances in fundamental theory\(^{160}\) have produced \( \text{ab initio} \) calculations of dilute gas transport properties for para-, ortho- and normal hydrogen from (20 to 2000) K\(^{161}\) that are as or more accurate than available measurements;\(^{162}\) however, these are only relevant for calculations involving low density gases. At higher densities, a reference viscosity model only exists for normal hydrogen\(^{163}\) in part because only one definitive data set for the viscosity of para-hydrogen exists.\(^{164}\)

Muzny et al.\(^{163}\) suggest that para-hydrogen’s viscosity is essentially equivalent to that of normal hydrogen provided the density is the same; for a given temperature, this correction can be facilitated using the Leachman et al. equations of state. The reference viscosity correlation for normal hydrogen has an estimated uncertainty of around 4% over the range (14 to 1000) K at pressures to 200 MPa, except in the critical region (where it is worse) and at pressures around 0.1 MPa (where it is better).

The thermal conductivity of para-hydrogen is nearly 30% larger than that of normal hydrogen at 140 K because of the heat capacity difference between the ortho and para spin isomers; this results from the higher rotational energy levels of the former.\(^{165}\) Assael et al.\(^{166}\) have developed reference correlations for the thermal conductivity of both normal and para-hydrogen, valid from the triple point to 1000 K and pressures to 100 MPa. Both correlations utilise the theoretical calculations of Mehl et al.\(^{161}\) for the dilute gas contribution. Critical enhancement contributions to thermal conductivity are more significant and wide-ranging (\( \approx 15 \text{ K} \) from the critical temperature) than they are for viscosity, and these are explicitly modelled for both normal and para-hydrogen. Thirteen data sets were considered primary for normal hydrogen, although only three extend below 273 K, and only one was measured below 77 K. For para-hydrogen, the data situation is worse with only two primary data sets, both measured by Roder\(^{167,168}\) covering (17 to 153) K and (99 to 274) K, respectively. Assael et al. estimated the relative combined expanded uncertainties of these correlations as follows: normal hydrogen ~ 4% for temperatures above 100 K
at pressures to 100 MPa, and 7% from the triple point to 100 K at pressures to 12 MPa, except in the critical region; para-hydrogen – 4% from the triple point to 300 K at pressures to 20 MPa, except in the critical region, and 6% at temperatures above 400 K. Differences in thermal conductivity have been used as a basis for measurements of the ortho–para ratio in a sample of hydrogen, particularly in the temperature range (50 to 250) K.

2.4 Conversion of ortho-hydrogen to para-hydrogen

In the absence of a heterogeneous catalyst, the ortho–para conversion occurs via a homogeneous auto-catalytic mechanism. In general, the conversion requires the presence of an inhomogeneous magnetic field (a magnetic field gradient), which exerts a torque upon the H₂ molecule inducing the required ‘spin-flip’. Given that para-hydrogen is non-magnetic, while ortho-hydrogen has a net local magnetic field, the rate of homogeneous ortho-to-para conversion is dictated by collisions between ortho-hydrogen molecules. The resulting transition rates are therefore dependent on the concentration and temperature of the ortho-hydrogen molecules present, and follow a second-order rate equation:\(^\text{169,170}\)

\[
\frac{dy_{\text{ortho}}}{dt} = -ky_{\text{ortho}}^2 + k'y_{\text{ortho}}(1 - y_{\text{ortho}}) \tag{3}
\]

\[
\tau = \frac{1}{k} \ln \left( \frac{y_{\text{ortho}}^{\text{eq}}}{y_{\text{ortho}}^{\text{eq}} - y_{\text{ortho}}} \right)
\frac{y_{\text{ortho}}^{\text{eq}}}{y_{\text{ortho}}^{\text{eq}} - y_{\text{ortho}}} \tag{4}
\]

Here \(\tau\) is the time needed to convert an initial ortho-hydrogen fraction, \(y_{\text{ortho}}\), to a final fraction, \(y_{\text{ortho}}^{\text{eq}}\), which is necessarily larger than the equilibrium fraction \(y_{\text{ortho}}^{\text{eq}}\). \(k\) and \(k'\) are the rate constants for the forward (ortho-to-para) and reverse (para-to-ortho) transitions, respectively. Milenko et al.\(^\text{169}\) measured \(k\) and \(k'\) for liquid and gaseous hydrogen from (16.65 to 120) K, at pressures up to 70 MPa. The conversion constants can be correlated:

\[
k = A_0 T^n \rho + (C_0 + D/T^m) \rho^q \tag{5}
\]

and

\[
k' = \frac{y_{\text{ortho}}^{\text{eq}}}{1 - y_{\text{ortho}}^{\text{eq}}} \tag{6}
\]

For \(k\) in unit of \(10^{-3} \text{ h}^{-1}\), \(A_0 = 18.2 \pm 1.6 \text{ cm}^3 \text{ kg}^{-1} \text{ h}^{-1} \text{ K}^{-n}; n = 0.56 \pm 0.02; C_0 = (38.5 \pm 1.5) \text{ cm}^3 \text{ g}^{-1} \text{ h}^{-1} \text{ K}^{-q}; D = (4.605 \pm 0.445) \text{ cm}^3 \text{ g}^{-1} 10^4 \text{ h}^{-1} \text{ K}^{-m}; m = 2.5 \pm 0.2\) and \(q = 3.6 \pm 0.6\). Fig. 3 shows the data of Milenko et al. together with the correlations presented in eqn (5) and (6). For the supercritical states relevant to hydrogen liquefaction, these results illustrate that while the conversion rate increases with both density and temperature, the time constants of the homogenous reaction are slow; the rate constants determined by Milenko et al. were determined from the time required to convert hydrogen samples from 75% to 68% ortho-hydrogen. Depending on the temperature and pressure, this degree of conversion took between 12 and 48 hours.

Such a slow conversion rate is unviable for industrial liquefaction processes, and thus heterogeneous catalyst materials are used to ensure that the ortho–para conversion occurs sufficiently quickly as the hydrogen is cooled down to 20 K. Solid catalysts convert the spin-isomers via one of several mechanisms; at the low temperatures relevant to hydrogen liquefaction, non-dissociative mechanisms where adsorbed hydrogen remains in its molecular form are of primary relevance. The two catalytic ortho–para conversion mechanisms most relevant to liquefaction processes are (i) spin-conversion at paramagnetic surfaces, and (ii) spin-conversion at magnetically ordered surfaces. The former involves the interaction of
hydrogen spin isomers with dilute paramagnetic species, such as Cr₂O₃, dispersed on high surface area materials such as alumina Al₂O₃. Chapin et al.¹⁷¹ found that the time constants of the ortho–para conversion reaction for H₂ at 77 K and pressures to 10 MPa increased by an order of magnitude in the presence of about 0.1 wt% Cr₂O₃ on Al₂O₃. Misono and Selwood¹⁷² showed how the application of external magnetic fields up to 0.8 T could further accelerate the conversion rate achieved with 0.03 wt% Cr₂O₃ on Al₂O₃ by a factor between 40 and 90 at 298 K and 173 K, respectively. Spectron Gas Control Systems previously offered a paramagnetic surface catalyst OXISORB® based on CrO for commercial applications. However since chromium has been banned for use in multiple jurisdictions as a result of safety considerations, it is no longer commercially available.

IONEX® is a commercially available catalyst used widely by industry for ortho–para conversion that functions via the mechanism of spin conversion at magnetically-ordered surfaces. Supplied by Molecular Products,¹⁷³ IONEX® is a porous particulate catalyst composed of Fe₂O₃ with a surface area around 216 m² g⁻¹ and particle (mesh) sizes between 0.3 and 0.6 mm.¹³⁴ Activation to remove adsorbed water is required prior to use via heating to 110–150 °C under vacuum or dry H₂ at 1 bar for one day. Exposure to trace impurities during operation can result in catalyst poisoning (H₂S, mercaptans) or gradual deactivation (N₂, H₂O, CO, NO).¹⁷⁴ Such impurities are, generally removed upstream by adsorption as they might otherwise freeze-out and cause a blockage.

Generally the kinetics of the ortho–para conversion in the presence of a heterogeneous catalyst are adequately described by first order kinetics of the form:¹⁷⁵–¹⁸⁰

\[
\frac{d\alpha}{dt} = k \cdot C_{\text{H}_2} \left( y_{\text{ortho}} - y_{\text{equil}} \right)
\]

Adaptation of eqn (7) using the Langmuir-Hinshelwood approach to account for the adsorption and desorption of hydrogen on the catalyst surface did not provide any significant improvement in agreement with experimental conversion data.¹⁷⁵–¹⁸⁰ Inclusion of external and internal mass transfer contributions to the overall reaction rate has been attempted via the inclusion of a catalyst effectiveness factor [e.g. Wakao et al.¹⁸¹] but this is an area requiring further investigation.

A few estimates of the inventory of catalyst required to convert a given amount of hydrogen are available in the open literature. Karlsson¹³⁴ used 37.5 kg of IONEX® catalyst to convert 24 kg of normal hydrogen in a flow loop at 20 K to 99.8% para-hydrogen within 4.75 minutes. Zhuzhgov et al.¹⁷⁴ estimated that approximately 65 L (or 80 kg) of an Fe₂O₃ catalyst (like IONEX®) is required to convert 100 kg h⁻¹ of normal hydrogen to 99% para-hydrogen at 21 K in a continuous flow reactor. They tabulate rate constants which allow calculation of the catalyst volume (or mass) required in a fixed bed reactor to treat a given feed flow of hydrogen to a specified outlet concentration of para-hydrogen. These average volume rate constants, which range from 0.24 mol s⁻¹ L⁻¹ at 78 K for Co(OH)₃ to 2.5 mol s⁻¹ L⁻¹ at 22 K for a NiO on Al₂O₃ catalyst, assumed first order kinetics and accounted for mass transfer limitations (and thus particle size) using the approach of Wakao et al.¹⁸¹ Assuming a fixed bed containing 65 L of an Fe₂O₃ catalyst at 21 K with a void fraction of 0.38, Zhuzhgov et al.¹⁷⁴ determined that a residence time of 4 s (liquid) and 400 s (gas) was required for effectively full conversion. This is a rate up to five orders of magnitude greater than that of the homogenous self-conversion reaction based on the data shown in Fig. 3. It is in fact likely that the ortho–para conversion kinetics in many practical scenarios are limited by heat transfer in terms of the removal of the heat of conversion.

Several research efforts focussed on improving ortho–para conversion efficiencies have been reported. One approach is to focus on alternative catalyst materials or properties. For example, Hutchinson¹⁷⁹ and Wilhelmsen et al.¹⁸² found that a nickel oxide–silica catalyst doubled the catalytic activity of iron(ni) oxide and reduced the cooling power consumption of the heat exchanger by 9%.¹⁸² Reducing the pressure drop associated with catalyst use within the liquefaction process is also an area of opportunity.¹⁸³ Park et al.¹⁸⁴ studied the pressure drop in a catalyst-packed heat exchanger using a cylinder filled with commercial IONEX® catalyst. It was found that the pressure drop is almost linearly dependent on space velocity (up to 1 bar pressure drop at velocity of 5 m s⁻¹) and approximately five times lower than that predicted using the Ergun equation.

Reducing such catalyst-induced pressure drops may prove to be a crucial feature of increased liquefaction efficiency.

Spectroscopic mechanisms of inducing the ortho–para conversion might also be worth considering. According to eqn (2), the smallest energy difference between the para- and ortho-states is approximately 28 K which corresponds to electromagnetic radiation with a frequency of 3.6 THz and a wavelength of 0.083 mm. It might then be possible to use the Purcell effect,¹⁸⁵ which is an enhancement of a molecule’s spontaneous emission rate by its environment, to accelerate the conversion of ortho- to para-hydrogen by incorporating the H₂ molecules within a cavity of length-scale 83 microns. In typical catalyst packings, many such micro-cavities are formed within the porous material. However, the cavities need to be electromagnetically resonant, and consideration would need to be given to the comparatively rapid diffusive motion of the gaseous hydrogen molecules and the associated effects such as Doppler linewidth broadening.

3 Hydrogen liquefaction
3.1 Fundamentals of hydrogen liquefaction
A generic hydrogen liquefaction process block diagram is shown in Fig. 4. Several recent publications cover hydrogen liquefaction methods¹³¹,¹³⁶–¹⁹⁰ so only a brief summary of the fundamentals is provided. If the hydrogen feed to the process is provided at comparatively low pressure, the first step of the process is pre-compression.¹⁹⁰ The hydrogen then undergoes an optional pre-cooling stage to 80 K and an adsorption stage to remove impurities that may freeze out during cryogenic
The hydrogen is then cooled to temperatures less than 30 K, using a closed-loop cryogenic refrigeration cycle. This cycle involves continuous or batch catalytic conversion of ortho to para-hydrogen. The final step is typically adiabatic expansion, which either takes the form of Joule–Thompson or turbine expansion. LH₂ is usually stored at 20–23 K (0.1–0.2 MPa) with a para-hydrogen fraction greater than 98%.

**Liquefaction cycles.** Three dominant types of hydrogen liquefaction system design or cycle are discussed in the literature: (i) Linde–Hampson cycle; (ii) Claude cycle; and (iii) Brayton refrigeration cycle. The Linde–Hampson is one of the oldest (1893) cycles used to liquefy gases and is characterised by low efficiency compared with other systems; it is only considered appropriate for small-scale (<2 TPD) systems. The initial gas compression provides the work used to liquefy the gas, which is cooled at near constant pressure by two heat exchangers, before undergoing Joule-Thompson expansion. The cold flashed vapour is used as a self-refrigerant in the second heat exchanger before being recycled to the feed. The Claude cycle improves the performance of this self-refrigeration process through the addition of an expander to cool part of the feed and increase the hydrogen coolant flow through the second heat exchanger. The Claude cycle is considered appropriate for large-scale systems (>2 TPD). Several modifications exist both in industry and the literature, which improve efficiencies by increasing the number of heat exchangers and/or through the use of nitrogen precooling. The Brayton refrigeration cycle uses a closed refrigeration loop containing nitrogen, helium, or a mixed refrigerant (MR) as the working fluid to cool the hydrogen stream. Historically, the Brayton refrigeration cycle has only been considered appropriate for small-scale plants; however, more recent literature has considered its expanded use in larger-scale systems.

**Efficiency parameters.** The specific energy consumption (SEC) of a given cycle is defined as the energy consumption per unit mass of hydrogen liquefied:

\[ w = \frac{W}{m} \]  

where \( w \) is specific energy consumption, \( W \) is net power consumption of the cycle, and \( m \) is the mass flow rate of product LH₂.

The second law of thermodynamics establishes that there exists a minimum possible SEC, related to the specific enthalpy change \( \Delta h \) and the associated specific entropy change \( \Delta s \) of the hydrogen as follows:

\[ w_{\text{ideal}} = \Delta h - T_0 \Delta s \]  

where \( T_0 \) is the ambient temperature. This evaluates to 3.9 kWh kg⁻¹ LH₂ given the following specifications:

- Inlet and outlet hydrogen pressure: 0.101 MPa;
- Inlet hydrogen temperature: 303 K;
- Ambient temperature: 298 K, and
- Inlet and outlet para-hydrogen mole fractions: 25% and 99.8%.

Exergy efficiency is a quantitative measure of the process efficiency and relates the actual SEC to the theoretical minimum value from eqn (9):

\[ \mu_{\text{ex}} = \frac{W_{\text{ideal}}}{w} \]  

where \( \mu_{\text{ex}} \) is the exergy efficiency of the liquefaction process or stage. An example distribution of total exergy for different stages in a hydrogen liquefaction process operating at various pressures is shown in Fig. 5 where most of the exergy is consumed in the cryogenic cooling stage.

**Process simulation.** The impact of thermodynamic property uncertainty on process simulations has been studied by multiple authors. A general conclusion is that new, high-quality data for multicomponent refrigerant mixtures are needed to improve the reliability of the equations of state used in process simulations, which in turn could reduce design margins and cost. Process simulation studies of conceptual liquefaction processes often use a variety of EOS with varying degrees of simplicity and computational efficiency traded-off with accuracy.
These studies have mostly been undertaken using commercial process simulation tools which permit detailed analysis of steady-state plant operation and the estimation of capital and operating costs for different design scenarios. For example, Cardella et al. optimized plant design using UniSim simulations incorporating a kinetic model for ortho-para conversion.210 Yin and Ju,214 Asadnia and Mehrpooya200 and Ansarinasab et al.219 all used Aspen HYSYS simulations to explore process optimization and the economics of hydrogen liquefaction. Yang et al.211 also using HYSYS, modelled the combined process of hydrogen production by steam methane reforming and liquefaction. Generally, the choice of simulation platform is less important than the fidelity of the models used to represent the physical properties of the hydrogen and refrigerant fluids, and the performance of key items of process equipment such as heat exchangers, turbines and compressors.

Valenti et al. assessed the influence of thermodynamic modelling on hydrogen liquefaction simulation outcomes of the Claude cycle.212 The study focused on the EOS for para-hydrogen and calculations of the heat capacity of equilibrium hydrogen (or para-hydrogen). The study found the following:

- Different EOS and heat capacity calculation methods yield significant differences in entropy (up to 11%) and exergy values (up to 13%).
- Adopting para-hydrogen models for the simulation of equilibrium hydrogen liquefaction may lead to errors greater than 10%.
- Densities calculated from the Peng–Robinson and Helmholtz-energy EOS models differed by up to 10%, with the largest differences found at low temperatures.

Collectively, heat capacity and density calculations had a major effect on the predicted cooling curves and are crucial for accurate and robust simulation of hydrogen liquefaction and subsequent equipment design.212 Furthermore, uncertainties in density at high pressure and/or liquid states result in uncertainties in volumetric flows. Erroneous volumetric flow predictions can lead to, for example, a mismatch of blade angles in turbo machinery, lowering efficiencies and, potentially leading to mis-predictions of operational range.

To demonstrate further the impact of thermodynamic property uncertainty on overall SEC, we have simulated a hydrogen liquefaction cryogenic process (hydrogen capacity: 5 TPD, $T$: 104 K to 20 K, $p$: 3 MPa) employing a basic Brayton refrigeration cycle with pure gaseous helium as the refrigerant ($T$: 104 K to 19 K, $p$: 8 MPa). The simulation determines the helium minimum flow rate needed to provide the required cooling, which significantly influences total compression power and thus SEC. Two different EOS have been applied for helium: the PR EOS and the reference Helmholtz EOS of Ortiz-Vega et al.214,215 The helium mass flow rate and SEC calculated using the two different EOS were 91 TPD vs 110 TPD (21% difference) and 5.5 kWh kg$^{-1}$ vs. 6.8 kWh kg$^{-1}$ (23% difference), respectively. These significant deviations are mainly caused by the different temperature drop determinations ($18.4$ K vs $16.6$ K) of helium across the vapour expander (isentropic efficiency: 78%), as obtained by the two EOS.

3.2 Industrial liquefaction processes and technology

The SEC of existing industrial hydrogen liquefiers ranges from (10 to 15) kWh kg$_{LH_2}$ or (35 to 45) % of the lower heating value of hydrogen,124–126 with exergy efficiencies ranging from 20–30%. This high energy demand is partially due to the relatively small size (capacity) of the existing liquefiers (less than approximately 32 TPD per liquefaction train), the design of which has focussed on lower capital cost (CAPEX) rather than high efficiency. This adds considerably to the cost and carbon intensity of the end-use hydrogen.216 More than fifty industrial hydrogen liquefaction plants have been constructed since 1952, with more than fifteen industrial plants constructed or proposed since 2000, as shown in Table 4. Recently-constructed plants are based on modified Claude cycles and use catalyst-packed heat exchangers (for continuous ortho-para conversion). Commercial catalysts are used in both the pre-cooling stage (where LN$_2$ is often used as the refrigerant) and the cryogenic stages before the final expansion. Only a small number of existing liquefiers are discussed in detail in the literature: examples include the Linde hydrogen liquefier at Leuna217 and Praxair large liquefaction plants218 in the USA.

**Linde-Leuna.** The Linde hydrogen liquefier (Fig. 6) at Leuna,217 Germany, is a modified pre-cooled Claude cycle where liquid nitrogen and hydrogen recycle stream are used in the pre-cooling and cryogenic stages, respectively. It reaches higher efficiency than a similar decommissioned plant at Ingolstadt.219 The improvements are due to the use of continuous ortho-para conversion, oil-free advanced dynamic gas bearing turbines and an ejector to re-liquefy boil-off gas and flash-gas. The cryogenic cooling system includes three turbines in series that operate between (0.52 and 2.0) MPa at 102,000 rpm.192,217 The reported SEC for the Leuna plant is 11.9 kWh kg$_{LH_2}$ and the exergy efficiency is 23.6%.131,217

**Praxair.** Praxair has five hydrogen liquefaction plants, all located in the USA, with capacities between 18 and 32 TPD.218 These plants also implement modified pre-cooled Claude cycles.
that include three heat exchangers (Fig. 7): the first cools the hydrogen feed with both nitrogen gas and a refrigerant from an external cycle, the second uses liquid nitrogen and the hydrogen recycle stream as coolants, while the third exchanger is cooled with the hydrogen recycle stream alone.\textsuperscript{189} The cryogenic cooling system includes two turbines, before a final isenthalpic (J–T) expansion. The plant includes continuous ortho to para conversion. Typical SEC values for the Praxair plants are between (12.5 and 15) kWh kg\textsubscript{LH\textsubscript{2}}/C\textsubscript{0}\textsuperscript{1} and the exergy efficiency is between (19.3 and 24)%.\textsuperscript{125}

3.3 Conceptual liquefaction processes and technology

Over 25 theoretical hydrogen liquefaction processes have been developed conceptually since 1987.\textsuperscript{200} The capacity of these conceptual plants ranges from (5 to 864) TPD. The SEC range of conceptual hydrogen liquefaction plants is 4–14 kWh kg\textsubscript{LH\textsubscript{2}}/C\textsubscript{0}\textsuperscript{1}. The objective of these conceptual models is to demonstrate theoretically how the efficiency of the liquefaction process can be optimised. Conceptual models do not in general fully

Table 4 Hydrogen liquefaction plants constructed within the last 20 years

<table>
<thead>
<tr>
<th>Location</th>
<th>Operator</th>
<th>Capacity [TPD]</th>
<th>Constructed</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kimitsu, Japan</td>
<td>Nippon Steel Corporation</td>
<td>0.2</td>
<td>2004</td>
<td>Pilot plant, separate H\textsubscript{2} from coke oven gas</td>
</tr>
<tr>
<td>Saggonda, India</td>
<td>Andhra sugars</td>
<td>1.2</td>
<td>2004</td>
<td>Constructed by Linde</td>
</tr>
<tr>
<td>Osaka, Japan</td>
<td>Iwatani [hydro-edge]</td>
<td>10</td>
<td>2006</td>
<td>Total capacity split between two units\textsuperscript{a}</td>
</tr>
<tr>
<td>Chiba, Japan</td>
<td>Linde</td>
<td>5</td>
<td>2008</td>
<td></td>
</tr>
<tr>
<td>Yamaguchi, Japan</td>
<td>Iwatani and Tokuyama</td>
<td>5\textsuperscript{a}</td>
<td>2009</td>
<td></td>
</tr>
<tr>
<td>Akashi, Japan</td>
<td>Kawasaki Heavy Industries</td>
<td>10</td>
<td>2013</td>
<td></td>
</tr>
<tr>
<td>Port of Hastings, Australia</td>
<td>HESC</td>
<td>0.25</td>
<td>2014</td>
<td>Japan's first domestically produced facility</td>
</tr>
<tr>
<td>Las Vegas, USA</td>
<td>Air liquide</td>
<td>27.2\textsuperscript{b}</td>
<td>2017</td>
<td>Capacity of existing plant doubled\textsuperscript{d}</td>
</tr>
<tr>
<td>Leuna, Germany</td>
<td>Linde</td>
<td>10</td>
<td>2020</td>
<td>Brampton's first H\textsubscript{2} liquefaction facility</td>
</tr>
<tr>
<td>Port of Hastings, Australia</td>
<td>Linde</td>
<td>10</td>
<td>2021</td>
<td>Capacity of existing plant doubled</td>
</tr>
<tr>
<td>La Porte, USA</td>
<td>Air products</td>
<td>27.2\textsuperscript{b}</td>
<td>2021</td>
<td>Praxair’s 5th H\textsubscript{2} liquefaction plant</td>
</tr>
<tr>
<td>California, USA</td>
<td>Air products</td>
<td>*</td>
<td>2021</td>
<td></td>
</tr>
<tr>
<td>Ulsan, Korea</td>
<td>Hyosung and Linde</td>
<td>13</td>
<td>2022</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a}Source did not state a value. \textsuperscript{b}Production capacity: 3000 L hour\textsuperscript{-1} per unit. \textsuperscript{c}Sources state US tons per day, values have been converted to metric tonnes per day. \textsuperscript{d}Construction was set to begin in 2020, source does not state an on-stream date.

Fig. 6 Process block diagram for the Linde hydrogen liquefier at Leuna.

Fig. 7 Process block diagram for a typical Praxair plant.

*Source did not state a value. \textsuperscript{b}Production capacity: 3000 L hour\textsuperscript{-1} per unit. \textsuperscript{c}Sources state US tons per day, values have been converted to metric tonnes per day. \textsuperscript{d}Construction was set to begin in 2020, source does not state an on-stream date.
consider total cost, operability or technical readiness.220 Large-scale hydrogen liquefaction methods and different configurations of hydrogen liquefaction cycles were reviewed by Aasadnia and Mehrpooya.131 Three of these conceptual designs proposed for large-scale hydrogen liquefaction process plans are summarised below.

**Ideally**. The IDEALHY project192,221 (Fig. 8) is a conceptual design of a 50 TPD liquefier based on an MR pre-cooled ‘nelium’ (75% helium, 25% neon) mixed refrigerant in a dual Brayton refrigeration cycle. Compression of the feed from (2 to 8) MPa occurs in two reciprocating piston compressors. Pre-cooling to 130 K is then achieved in four heat exchangers using a MR comprising nitrogen, methane, ethane, propane, and n-butane. Cryogenic cooling is performed by two overlapping Brayton cycles using nelium. Ortho to para conversion occurs during the pre-cooling stage (130 to 85) K in four adiabatic converters and then continuously in subsequent catalyst-packed heat exchangers (<85 K). Final expansion of the hydrogen stream to the liquid phase is achieved through two expansion turbines from (8 to 0.2) MPa. The outlet stream of the final turbine includes hydrogen flash gas. The SEC and exergy efficiency of this process are 6.7 kWh kg\textsubscript{LH\textsubscript{2}} and 32%, respectively. According to Cardella, the SEC increases to approximately 7.8–8.2 kWh kg\textsubscript{LH\textsubscript{2}} if the feed compression is considered.126 The IDEALHY project found that heat integration with an adjacent LNG import and regasification terminal could reduce the SEC by 0.62 kWh kg\textsubscript{LH\textsubscript{2}}.221

**Kuendig et al.** The model shown in Fig. 9235 is a conceptual design of a 50 TPD liquefier based on a Claude cycle with pre-cooling by LNG and nitrogen gas. LNG was selected as the working fluid because of its potential availability at the liquefaction site and its possible use for hydrogen production via steam methane reforming. The concept also exploits the idea of using LNG re-gasification at an import terminal to provide pre-cooling and therefore reduce the SEC of the hydrogen liquefaction process. The hydrogen feed undergoes pre-cooling from 300 K to 80 K via three heat exchangers with
(1) LNG, (2) nitrogen gas, and (3) liquid nitrogen. Hydrogen then passes through a final purification stage before entering an ortho-para conversion reactor (from ~25% to 42.7% para-hydrogen). Further cooling to 26 K is achieved in five catalyst-packed heat exchangers and seven hydrogen-gas-bearing turbines arranged in three strings. The SEC efficiency of this process is 4 kWh kg LH₂⁻¹. The concept is dependent on the availability of LNG, its requirement to be regasified on site, and that it may be used at no additional cost. A similar concept using LNG for pre-cooling was proposed by Shigekiyo.236

**HP-H₂ cycle with MRC.** This 100 TPD hydrogen liquefaction process concept proposed by Cardella et al.210 (Fig. 10) is designed with a mixed-refrigerant Joule–Thomson precooling cycle and a high-pressure hydrogen Claude cycle for cryogenic cooling and liquefaction. This modified Claude cycle design is optimised for large-scale liquefaction using available oil-free hydrogen reciprocating piston compressors. High-speed oil or gas bearing cryogenic hydrogen turbo expanders can be implemented into this design with the option of energy recovery via turbine-generators. The refrigerant compositions were optimized using 4 components and were comprised of a blend of nitrogen with up to three C1 to C5 hydrocarbons. The SEC and exergy efficiency of this process are 6.2 kWh kg LH₂⁻¹ and 43%, respectively. According to Cardella et al.,210 a specific energy consumption below 6 kWh kg LH₂⁻¹ could be achieved while reducing the specific liquefaction costs by 67% compared to smaller scale 5 TPD LH₂ plants; this process could be implemented in the next few years making it one of the most promising conceptual design currently available. A similar concept using LNG for pre-cooling was proposed by Shigekiyo.236

**3.4 Technical gap between actual and conceptual units**

Conceptual plants are designed to provide lower SEC and higher exergy efficiency, as summarised in Fig. 11.126 However, limited consideration is given to total installed and operational costs or the technical maturity and ability to scale-up the component unit operations. This is particular true with respect to selection of the appropriate compressor type and the size of the required cold box.220 Current designs for approved future hydrogen liquefiers do not exceed the single liquefaction train capacity of approximately 30 TPD. Conceptual plants designed to be larger than 50 TPD thus help identify the required knowledge gaps and technological advances required for hydrogen liquefaction production at these elevated scales with improved SEC and exergy efficiency.

A selection of potentially feasible conceptual hydrogen liquefaction processes are detailed and compared in Table 5.
Hydrogen feed gas is often compressed to higher pressures to enhance liquefaction. Compression to higher feed pressures can reduce the work needed downstream,202 however, feed conditions are limited by the maximum allowable operating pressure of available heat exchangers.202 Compressors used for both feed compression and in the refrigeration cycle account for the largest proportion of overall power consumed (90% or more).126,192 Stage compression and in the refrigeration cycle account for the largest proportion of overall power consumed (90% or more).126,192 Turbo-compressors generally have higher efficiency and greater throughput than piston compressors and are more suitable for large scale liquefaction. However, turbo-compressors are only really feasible for use with gases with molar masses above approximately 6 g mol⁻¹.192 For pure hydrogen, a large number of turbo-compressor stages are required to reach the desired pressure as shown by Quack81 and Valenti and Macchi,216,239 and thus would incur higher capital expenditure. For example, the compression of hydrogen gas from atmospheric pressure to 8 MPa using a turbo-compressor would require at least 24 stages.202 Turbo-compressors are better suited to installation on the refrigerant side of the liquefaction process, as the refrigerant typically has a higher molar mass than hydrogen.239 There is no evidence of turbo compressors currently being used in industrial hydrogen liquefaction plants.192

Pre-cooling. This is commonly used in both established and conceptual designs to improve liquefaction efficiency.155 Krasae-in found that the addition of a pre-cooling stage reduced the compressor power required by the Claude cycle by (5 to 10)%; however, additional heat exchangers and a more expensive expander were required.155 Pre-cooling is a hallmark of all industrial and conceptual process in Table 5. While nitrogen is the only pre-cooling fluid used in known commercial hydrogen liquefaction plants, conceptual cycles use nitrogen, propane, MRs, and LNG as the relevant working fluid.

Heat exchangers. Plate-fin heat exchangers (PFHE, Fig. 12) are used in industrial hydrogen liquefiers because of their high flexibility concerning the number of process channels (and hence capacity), large heat exchange surface area (>2000 m² m⁻³ possible245) coupled with comparatively small footprint, and comparatively low CAPEX.188,216,243 Process passages in the heat exchangers are often packed with particulate ortho–para conversion catalysts. Aluminium is the most common material used for these cryogenic heat exchangers, due to its comparatively high thermal conductivity and strength at low temperatures.192,243,244 Such plate and fin heat exchangers are typically designed for pressures up to approximately 13 MPa.192

A larger heat exchange surface area and volume can deliver higher exergy efficiency but imposes higher capital expenses.245,246 The overall heat exchanger size is, however, limited primarily by the size of the accommodating coldbox and, to a lesser extent, the design pressure. Conceptual plants designed for large scale may need to address potential challenges with respect to process fluid pressure drop through the catalyst packings.183,184,216,247 Linde reported that the maximum size for LH₂ industrial heat exchangers is approximately 8.2 m × 3.4 m × 1.5 m, with a core volume of 15 to 30 m³ and a specific surface of (500 to 2000) m² m⁻³.242 These reported maximum
### Table 5: Conceptual and Established Hydrogen Liquefaction Processes Developed within the Last 20 Years, Sorted according to Capacity

<table>
<thead>
<tr>
<th>Project</th>
<th>Linde – Leuna, 2007¹²⁷,²¹⁷,²¹⁸</th>
<th>Praxair – USA¹²³,¹⁸⁹,²¹⁸</th>
<th>IDEALHY, 2013¹³²,²²¹</th>
<th>Berstad et al, 2010¹³⁷</th>
<th>Krase-in, 2014²³⁸</th>
<th>QUACK, 2002¹²⁷,²³⁹</th>
<th>WE-NET, 2004⁴⁹⁰,²¹⁰</th>
<th>HP-H₂, 2017¹¹⁰</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Liquefaction cycle</strong></td>
<td>LN₂ pre-cooled Claude</td>
<td>N₂ pre-cooled Claude</td>
<td>MR pre-cooled Brayton</td>
<td>MR pre-cooled Brayton</td>
<td>MR pre-cooled Brayton</td>
<td>MR pre-cooled Brayton</td>
<td>LN₂ pre-cooled Claude</td>
<td>MR pre-cooled Claude</td>
</tr>
<tr>
<td><strong>Capacity [TPD]</strong></td>
<td>5</td>
<td>20–36³</td>
<td>67</td>
<td>86</td>
<td>100</td>
<td>170</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td><strong>SEC [kWh kg⁻¹H₂]</strong></td>
<td>11.9</td>
<td>12.5–15</td>
<td>6.7</td>
<td>6.15–6.51</td>
<td>5.91</td>
<td>6.93</td>
<td>8.53</td>
<td>6.2</td>
</tr>
<tr>
<td><strong>Exergy efficiency</strong></td>
<td>23.6%</td>
<td>19–24%</td>
<td>32%</td>
<td>44.7–47.1%</td>
<td>39.1%</td>
<td>56.8%</td>
<td>46%</td>
<td>43%</td>
</tr>
<tr>
<td><strong>Hydrogen feed</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pressure [MPa]</strong></td>
<td>2.4</td>
<td>*</td>
<td>2</td>
<td>2</td>
<td>310</td>
<td>8</td>
<td>3.04</td>
<td>*</td>
</tr>
<tr>
<td><strong>Temperature [K]</strong></td>
<td>313</td>
<td>*</td>
<td>293</td>
<td>310</td>
<td>298</td>
<td>300</td>
<td>300</td>
<td>303</td>
</tr>
<tr>
<td>para-H₂³</td>
<td>*</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
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<tr>
<td><strong>Compression</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pressure [MPa]</strong></td>
<td>—</td>
<td>*</td>
<td>8</td>
<td>8</td>
<td>—</td>
<td>8</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td><strong>Compressor type</strong></td>
<td>—</td>
<td>*</td>
<td>Piston [2-stage]</td>
<td>Piston</td>
<td>—</td>
<td>Piston</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>*</td>
<td>85%</td>
<td>85%</td>
<td>85%</td>
<td>85%</td>
<td>85%</td>
<td>80%</td>
<td>—</td>
</tr>
<tr>
<td><strong>Pre-cooling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Refrigerant</strong></td>
<td>Nitrogen</td>
<td>Nitrogen</td>
<td>Multi-component²</td>
<td>Multi-component²</td>
<td>Vapour/MR²</td>
<td>Nitrogen</td>
<td>MR</td>
<td>MRC²</td>
</tr>
<tr>
<td><strong>Refrigerant cycle</strong></td>
<td>LN₂ evaporation</td>
<td>GN₂ &amp; LN₂ evaporation²</td>
<td>MR closed loop</td>
<td>3 stage MR</td>
<td>2 stage MR</td>
<td>LN₂ evaporation²</td>
<td>MR</td>
<td>MRC²</td>
</tr>
<tr>
<td><strong>Temperature [K]</strong></td>
<td>80</td>
<td>80</td>
<td>130</td>
<td>75</td>
<td>80</td>
<td>80</td>
<td>100</td>
<td></td>
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<tr>
<td><strong>Cryogenic cooling</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Refrigerant</strong></td>
<td>Hydrogen</td>
<td>Hydrogen</td>
<td>Hydrogen</td>
<td>Hydrogen</td>
<td>Hydrogen</td>
<td>Hydrogen</td>
<td>Hydrogen</td>
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<tr>
<td><strong>Refrigeration cycle</strong></td>
<td>Claude</td>
<td>Claude</td>
<td>Brayton</td>
<td>Brayton</td>
<td>Brayton</td>
<td>Brayton</td>
<td>Brayton</td>
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<tr>
<td><strong>Temperature [K]</strong></td>
<td>*</td>
<td>*</td>
<td>26.8</td>
<td>26.5</td>
<td>20</td>
<td>25</td>
<td>*</td>
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<td><strong>Compressor type</strong></td>
<td>Piston</td>
<td>*</td>
<td>Turbo</td>
<td>Turbo</td>
<td>*</td>
<td>Turbo</td>
<td>Piston</td>
<td></td>
</tr>
<tr>
<td><strong>Compressor stages</strong></td>
<td>2 × 2</td>
<td>*</td>
<td>6</td>
<td>15</td>
<td>8</td>
<td>8</td>
<td>15/25</td>
<td>2²</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>65–70%⁹</td>
<td>*</td>
<td>85%¹</td>
<td>85%¹</td>
<td>90%¹</td>
<td>85%</td>
<td>80%¹</td>
<td>76–85%</td>
</tr>
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<td><strong>Expander type</strong></td>
<td>Turbo</td>
<td>*</td>
<td>Turbo</td>
<td>Turbo</td>
<td>*</td>
<td>Turbo</td>
<td>Centrifugal</td>
<td>Turbo</td>
</tr>
<tr>
<td><strong>No. of expanders</strong></td>
<td>3</td>
<td>*</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>2</td>
<td>*</td>
</tr>
<tr>
<td><strong>Expander efficiency</strong></td>
<td>&gt;85%¹</td>
<td>*</td>
<td>80%¹</td>
<td>90%¹</td>
<td>90%¹</td>
<td>85%¹</td>
<td>78–88%</td>
<td></td>
</tr>
<tr>
<td><strong>O–P conversion</strong></td>
<td>Continuous</td>
<td>Continuous</td>
<td>Batch and continuous</td>
<td>Continuous</td>
<td>6 stages</td>
<td>Continuous</td>
<td>Partially continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td><strong>Expansion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Isentropic efficiency</strong></td>
<td>N/A</td>
<td>N/A</td>
<td>80%¹</td>
<td>85%</td>
<td>Expander &amp; J–T²</td>
<td>85%</td>
<td>78–88%</td>
<td></td>
</tr>
<tr>
<td><strong>Liquid H₂ product</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pressure [MPa]</strong></td>
<td>0.13</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Temperature [K]</strong></td>
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<td>20.2</td>
<td>22.8</td>
<td>20.2</td>
<td>19.5</td>
<td>20.2</td>
<td>20.4</td>
<td>22.8²</td>
</tr>
<tr>
<td>para-H₂³</td>
<td>&gt;95%</td>
<td>&gt;95%</td>
<td>&gt;98%</td>
<td>&gt;98.5%</td>
<td>95%</td>
<td>&gt;99%</td>
<td>&gt;95%</td>
<td>&gt;98%</td>
</tr>
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</table>

*The study did not provide data for this value. ¹ Conceptual – presented in research, not yet proven. ² Modified pre-cooled Claude cycle with 3 heat exchangers. The first: nitrogen gas [GN₂]a n dH₂ recycle stream, second: liquid nitrogen [LN₂]a n dH₂ recycle stream, third: H₂ recycle stream. Established – process has been implemented at scale. ³ Four cascaded hydrogen Joule–Brayton cycles pre-cooled with a multi-component refrigerant. ⁴ The largest capacity plant is a double-train liquefier. ⁵ Includes auxiliary plant energy requirements. ⁶ Dead-state temperature modified from 288.15 K to 300 K. ⁷ para-hydrogen percentage composition. ⁸ Main compressor stage efficiency assumed where source has not specifically stated a value. ⁹ Unknown category of efficiency. ¹⁰ Isentropic efficiency. ¹¹ Multi-component mixture contains five components: hydrogen, nitrogen, methane, ethane and butane. ¹² Two vapour compression refrigeration cycles used, propane to cool to 220 K and MR to cool to 73 K. ¹³ Liquid nitrogen at 0.12 MPa. ¹⁴ 15 stages required for low pressure and 25 required for high pressure. ¹⁵ Isothermal efficiency. ¹⁶ Polytropic efficiency. ¹⁷ J–T – Joule–Thomson valve. ¹⁸ J–T valves produce a SEC and an exergy efficiency of 6.5 kWh kg⁻¹ and 44.7%, respectively. Liquid expanders produce a SEC and an exergy efficiency of 6.15 kWh kg⁻¹ and 47.1%, respectively.
Feasible geometrical dimensions represent a potential limitation to up-scaling of efficient hydrogen liquefaction processes. However, PFHE remain the preferred technology for large-scaled hydrogen liquefaction. Skaugen et al. considered the use of spiral-wound heat exchangers for LH2 production with a capacity of 125 TPD. The lower surface density area and heat transfer coefficients in the spiral-wound heat exchangers meant their required weights are 2 to 14 times higher than those of the plate-fin heat exchangers.

Recently-built industrial hydrogen liqueifiers and most conceptual processes in the literature employ continuous catalytic ortho–para conversion. A more thermodynamically efficient conversion that maintains the ortho–para ratio close to its equilibrium value can be achieved in such continuous catalytic conversion arrangements because both sensible and conversion heat are removed concurrently in the heat exchanger, resulting in higher exergy efficiency.

Key limitations regarding heat exchanger design are excessive pressure drop through the catalyst bed and the ability to model quantitatively conversion kinetics while incorporating relevant heat and mass transfer limitations. Some conceptual processes use multiple stages of batch conversion to mimic continuous conversion largely because of the difficulty in quantifying the conversion kinetics.

**Refrigerants.** Existing liqueifiers only use nitrogen in the precooling stage while a hydrogen recycle stream is used in the cryogenic stage. Nitrogen is often a readily available fluid because hydrogen liqueifiers are frequently sited close to air separation plants. When liquid nitrogen is not readily available and the power required to produce liquid nitrogen is considered (<0.5 kWh kg⁻¹), the efficiency advantage of liquid nitrogen pre-cooling decreases. For example, Van Hoecke et al. estimated that 30% of the energy required for the liquefaction of hydrogen is used to produce liquid nitrogen. A challenge with using nitrogen is, however, the large temperature differential between its cooling curve and that of the pre-cooled hydrogen gas which limits heat recovery. Conceptual processes have accordingly explored the use of helium, neon, LNG, and mixed refrigerants in both pre-cooling and cryogenic stages. Mixed refrigerants (MRs) are advantageous because the evaporation curve can be designed to closely match the cooling curve of the hydrogen gas by altering the refrigerant mixture’s composition. The resulting minimisation of temperature difference improves thermodynamic efficiency. Mixtures may also have better heat transfer properties and compression features than pure refrigerants.

Common MR compositions include hydrogen, nitrogen, neon, helium, and hydrocarbons ranging from methane to butane. However, achieving the desired hydrogen effluent temperature of 80 K in one stage, and the potential freeze-out of the heaviest components in the refrigerants are limitations. Thus conceptual processes have proposed a higher pre-cooling temperature, for example, 130 K, with multi-stage cascaded removal of components based on temperature. While implemented in LNG liquefaction, this can be challenging given the need to control and optimise the composition of the MRs throughout the cooling process. Improved thermodynamic modelling of novel mixed refrigerants is needed to compare their performance with simple conventional refrigerants. Based on LNG experience, research into the optimal blending of these fluids and methods aimed at preventing the refrigerant mixture components from segregating is required.

**Expansion.** Cooling can be achieved via Joule–Thompson expansion through a throttle valve or by turbine expansion.
which enables further cooling with increased CAPEX. The use of turbine expanders results in higher exergy efficiency because mechanical energy from the rotation of the turbine can be recovered and a larger cooling effect is achieved. This could potentially reduce specific energy consumption by about 7% or more. Radial flow turbines and axial flow turbines are used for industrial liquefer expansion on the refrigeration side. Reported cryogenic expander efficiencies in the literature are between (80 and 90)%. Axial turbines have a higher efficiency than radial turbines (at Re > 10⁴), but attract a higher capital cost. Radial turbines are advantageous in that the work recovered from a single stage is equivalent to that of two or more stages in an axial turbine.

Oil-bearing and gas-bearing turbine technologies are considered state-of-the-art for hydrogen liquefiers. Oil-bearing systems require a continuous oil supply, oil pumps, and additional infrastructure for safe shutdown in the case of cycle failure. Additional equipment and power requirement increases their capital and operational expenditure above those of gas-bearing turbines. Gas-bearing turbines eliminate the risk of oil contaminating the hydrogen (because they use a gas film in the bearings), have higher isentropic efficiencies than oil-bearing turbines, reduced footprint, and provide greater turbine reliability.

Most of the conceptual processes identified in Table 5 utilise a turbine expander both on the hydrogen and refrigeration side; however little detail as to the type to be deployed is provided. Valenti and Macchi estimated power recovery from expanders in their helium Brayton cycle to be greater than 1 kWh kg⁻¹. There is certainly potential to use large oil-free turbines in large-scale liquefiers; however, turbine expanders are both complex and attract a higher capital expenditure. Alternatively, exposing hydrogen to external magnetic fields can cause a temperature change and potentially liquefy it. Consequently, recent studies have considered the use of magnetic refrigeration as a final cooling stage in place of expansion to liquefy the hydrogen.

Liquefaction cycles. To date, industrial liquefiers has been limited to pre-cooled Claude cycles. Conceptual liquefaction processes employing Brayton refrigeration cycles with high compressor and expander efficiencies (Berstad et al., Valenti & Macchi, IDEALHY, Krasae-in) are often characterised by higher exergy efficiencies and lower SEC. The use of MRs on the working fluid side, as opposed to hydrogen, has been found to reduce the overall exergy destruction by 7%.

Further research into the viability of large scale Brayton cycles is warranted.

3.5 Cost gap between existing and conceptual plants

Energy use accounts for around 30% of the total liquefaction cost of current liquefiers. These are dependent mainly on the liquefer efficiency which is in turn highly dependent on the energy consumption of the selected liquefaction process and electricity price. Liquefaction capacity also plays a major role in the cost breakdown. While existing liquefiers produce liquid hydrogen at (2.5 and 3) US$ per kg, some conceptual designs are projected to produce liquid hydrogen below 1 US$ per kg. Literature liquefaction cost estimates, as shown in Table 6 and Fig. 14, provide insight into plausible target costs. The Asia Pacific Energy Research Centre (APEC) report includes a projected hydrogen liquefaction price between (0.5 and 0.8) US$ per kg. This cost is much smaller than current liquefiers and is based on the IDEALHY system which estimates an energy consumption of approximately 6.4 kWh kg⁻¹.

To date, such efficiency has not yet been achieved in commercial liquefiers. In comparison, Kawasaki Heavy Industries has stated a liquefaction price of approximately 9.8 JPY per Nm³ (1.1 US$ per kgH₂). Wijayanta et al. projected a smaller liquefaction cost by 2030 of approximately 7.3 JPY per Nm³ (0.76 US$ per kgH₂). Other cost estimates are detailed in Table 6. However, none of the cost estimates can be achieved using existing liquefier designs, capacities and technologies. For reference, Connelly et al. estimated a liquefaction cost of 2.75 US$ per kgH₂ for a 27 TPD plant in California (USA), which is based on current commercially available technology used in existing industrial liquefiers. As shown in Fig. 14, specific liquefaction costs generally decrease with increasing plant capacity; however, this depends largely on the electricity cost which varied between (40 and 120) US$ per MW h across these studies. This observation is consistent with the work published by Cardella et al. who found that SLC decreased by almost 60% with a 50 TPD plant or by 67% with a 100 TPD plant, compared with a 5 TPD plant.

3.6 Development potential of large-scale LH₂ plants

From the above review of industrial and conceptual hydrogen liquefaction plants, key challenges were identified across the liquefaction process; these are summarised in Table 7. Obviously, for a new generation of large-scale plants (>100 TPD), there is a need to increase efficiency while managing overall total cost – a SEC target of 6 kWh kg⁻¹ and a SLC less than 1 US$ per kg should be achievable.

A specific power requirement range between (6 and 8) kWh kg⁻¹ is a plausible target, as shown in Fig. 14 by various conceptual studies, for scaled-up liquefiers without the need for novel technologies. However, this should be obtained via identifying rational and economically-credible means for improving efficiency which necessitates more advanced and integrated process designs that can increase exergy efficiency and thus reduce specific power requirements. Different design features should be considered in comparison to traditional large-scale hydrogen liquefaction processes, such as:

- Use of liquefaction cycles with new cryogenic refrigerant mixtures of helium/neon/hydrogen to enable the use of turbo compressors, which are generally well suited and scalable to very high capacities. This, and the potential for higher compressor efficiency, could be important elements when scaling-up liquefaction plants.

- Similarly, use of MR/LNG in the pre-cooled cycle instead of nitrogen to potentially cool down the hydrogen to around (80–110) K. Although some consideration is still required with respect to potential freeze-out and optimized composition, this
can be largely implemented today. This can be accompanied by the use of expanders to increase efficiency.

- In addition use of, high-efficiency turbo-compressors on the refrigeration side, replacement of the J–T valve at the liquefaction stage by an expansion gas-bearing turbine (to minimize vapor fraction after expansion) whilst also ensuring high feed gas pressures between (1.5 and 3) MPa.

### 4 Liquid hydrogen storage and transportation

Rising demand for liquid hydrogen in new markets located a long-distance from the production site presents a new set of challenges in terms of transport and storage of this cryogenic fluid. These challenges stem largely from the boil-off losses caused by various heat sources leaking into the liquid, particularly over long periods of time. The severity of the problem was demonstrated in the Space Shuttle program managed by NASA, where over 24,500 tonnes of liquid hydrogen were purchased, of which 45.4% was lost during storage, loading, or replenishing.

#### 4.1 Liquid hydrogen storage

**Tank design – shape.** Liquid hydrogen is most commonly stored in horizontal or vertical cylindrical tanks. Fig. 15 schematically shows the general features of a traditional LH₂ storage tank regardless of shape or scale. Structural supports can be based on tension (rods or cables) or compression (load bearing pads) depending on the particular tank design. Ullage space is typically ≤10% of the internal volume of the tank.

Spherical tanks are used for storing larger volumes because they provide a minimum surface-to-volume ratio, and a more uniform distribution of stresses and strains. NASA operates the largest current storage vessel (3800 m³) for liquid hydrogen at Kennedy Space Centre, FL, USA with a storage capacity of 263 tonnes (if stored at 22 K and 0.15 MPa). NASA has more recently announced the construction of a 4732 m³, 327 tonne liquid hydrogen tank. In 2015 the US Department of Energy reported the price for a 3500 m³ liquid hydrogen tank was US$6.6 million (with a long-term target price of US$3.3 million).

Kawasaki Heavy Industries completed the construction of its LH₂ receiving terminal in the Port of Kobe in July 2020.
terminal features a 2500 m$^3$ double-shell spherical storage tank with an outer diameter of approximately 19 m.\textsuperscript{267} The tank contains vacuum perlite insulation and is designed for a boil-off rate of less than 0.1\% per day.\textsuperscript{267} Linde provides a variety of liquid hydrogen storage tank designs for industrial applications, fuel stations and bulk storage. These range in size from (12 to 300) m$^3$, with a boil-off rate of $\text{<}0.95\%$ per day, depending mainly on the insulation materials used (vacuum-perlite or multi-layer insulation).\textsuperscript{268} Linde’s large spherical tanks have an inner volume of 1100–2300 m$^3$ with a storage capacity of 70–145 tonnes LH$_2$ and a boil-off rate of $\text{<}0.1\%$ per day.\textsuperscript{268}

**Tank design – material.** The selection of a suitable tank wall material requires a balance of high strength, high fracture toughness, high stiffness, compatibility with cryogenic temperatures, and low permeation of liquid and gaseous hydrogen.\textsuperscript{269} The most appropriate materials for the construction of inner tanks are metallic materials and composites.\textsuperscript{269} Metals with acceptable properties from ambient to cryogenic temperatures include austenitic stainless steels, monels, aluminium alloys, titanium, and copper.\textsuperscript{269} 300-series stainless-steel alloys are most commonly used in industry for inner vessel walls, with carbon steels used for outer vacuum shells. Ceramic materials offer high specific strength but, owing to their low fracture toughness, are not appropriate.\textsuperscript{269}

In applications where weight is an issue, tank designs must also minimise tank weight. Tanks can, for example, exceed 50\% of the dry weight of a space vehicle.\textsuperscript{270} Typical vessel designs are double-walled, vacuum-jacketed fluid containers.\textsuperscript{271,272} However, tanks may also use single walls with constant or variable thicknesses, although these are primarily employed at end-use points such as for rocket propellant tanks, and not for long term storage. High-vacuum insulation ($\text{<}10^{-2}$ Pa) is commonly used for small-sized tanks (40 m$^3$) and low-vacuum insulation ($\text{<}1$ Pa) is used for large tanks.\textsuperscript{102} The space between the double-walls serves as an insulation layer to minimise heat transfer to the liquid hydrogen in the inner vessel – traditionally perlite is used in this capacity. Advantages and disadvantages of common insulation methods are set out in Table 8.

A number of composite wall materials have also been investigated, including graphite/epoxy composites and composite
Challenges in the application of these materials include significant thermal residual stress in laminates due to coefficient of thermal expansion (CTE) mismatch between fibres and resin, and the embrittlement of stress in laminates due to coefficient of thermal expansion (CTE) mismatch of these materials.92 Research is still ongoing into the permeability and micro-cracking of these materials.92

Glass bubble insulation consisting of hollow glass spheres has been proposed. Field demonstration tests at NASA’s Kennedy and Stennis Space Centres in 2015 found that boil-off losses were reduced by as much as 46% through the use of this glass bubble insulation in the field, compared to the use of perlite. Aerogel insulation may be feasible for short-term storage.273 Liquid hydrogen storage vessels manufactured with a liquid nitrogen shield have been proposed. Another design concept is to use the cold hydrogen boil-off vapor to shield the stored liquid hydrogen, resulting in a warmer gas exiting the tank.274

At the large scales planned for the future (> 50 000 m³), the biggest issue associated with liquid hydrogen storage is likely to be how to appropriately insulate the vessels. Traditional vacuum-jacketing might not be feasible at this scale. Novel insulation system schemes are needed that don’t require a self-supported outer jacket, but which still meet the thermal performance requirements associated with managing boil-off gases, preventing air liquefaction (if exposed to the environment), gas purge requirements, and which do not degrade over time.

**Boil off management.** Boil-off gas (BOG) production is an unavoidable result of the storage of LH₂.133,275,276 A certain percentage of liquid hydrogen will enter the gas phase over time depending on factors such as wall material, insulation quality and surface-to-volume ratio of the vessel. While there are analogies with the storage of other industrially important cryogenic liquids, like LNG and LN₂, BOG is much more severe for LH₂ given it is stored at temperatures about 90 K lower. Liquid hydrogen BOG losses can be on the order of 0.4% per day for a 50 m³ cryogenic tank, and 0.06% per day for a 20 000 m³ tank.271 Additionally, heat ingress causes the vapor temperature to increase faster than that of the liquid due to the vapor’s higher thermal diffusivity, resulting in heat conduction across the vapor–liquid interface and thus a temperature gradient in the top layer of the liquid phase known as thermal stratification.277–285

BOG generation occurs at LH₂ plants and exporting terminal for several additional reasons. These include BOG generation due to depressurisation (flashing), heat ingress into transfer pipes, heat added by equipment such as pumps, and cooling down of LH₂ carrying vessels. For future large-scale LH₂ storage and transport applications involving land-based tanks and
sea-borne vessels, the management of such BOG is crucial from both an economic and safety perspective.

Petitpas\textsuperscript{276} modified a MATLAB code previously provided by NASA, to estimate the boil-off losses along the entire LH\textsubscript{2} pathway from liquefaction to dispensing. During LH\textsubscript{2} storage, Petitpas found that some temperature gradients may exist across the vessel (thermal stratification). This tendency of the stored liquid hydrogen to thermally stratify in a layer near the liquid-vapor interface causes challenges in propellant utilisation in large liquid-hydrogen fuelled rocket vehicles where pump cavitation is likely to occur which could result in the destruction of the flight vehicle.\textsuperscript{278} Fig. 16 shows a comparison between calculations made by their code for a 12.5 m\textsuperscript{3} storage vertical tank (90% fill, with initial and final (relief) pressure of 0.137 and 0.31 MPa, respectively) and the super-heated vapour BOG model developed recently at UWA,\textsuperscript{286–288} originally for simulating industrial-scale LNG storage. This super-heated vapour model, implemented in the freely-available software package BoilFAST which includes options for LH\textsubscript{2} and NH\textsubscript{3} storage,\textsuperscript{289} considers the vapor and liquid phase temperatures to be independent but assumes they are spatially uniform; the liquid phase is assumed to be saturated, while the vapor can become superheated. For each phase, mass and energy balances are solved iteratively to determine phase amount and composition, boil-off rate, and vapor temperature. The BoilFAST results for the 12.5 m\textsuperscript{3} LH\textsubscript{2} storage tank were in excellent agreement with those calculated by Petitpas and provided additional predictions such as BOG relief rate. On average, the daily BOG amount was calculated by both methods to be 5 kg (less than 0.5% volume loss per day).

Many studies\textsuperscript{290–303} have investigated possible ways to reduce boil-off losses and suggested that top fill (top spray) is probably the most effective way to reduce transfer losses, although more understanding of the underlying physics is needed. NASA have demonstrated the operation of an Integrated Refrigeration and Storage (IRAS)\textsuperscript{294} system allowing temperature control of the stored liquid hydrogen. This system employs an integrated heat exchanger together with a cryogenic refrigeration

<table>
<thead>
<tr>
<th>Insulation method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
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<tbody>
<tr>
<td>Foam – outside</td>
<td>+ Currently in use, well established</td>
<td>– Short term storage applications due to high thermal conductivity</td>
</tr>
<tr>
<td></td>
<td>+ Low cost, easy to implement</td>
<td>– Low resistance to thermal radiation</td>
</tr>
<tr>
<td></td>
<td>+ Lightweight and low density</td>
<td>– Potential damage from environmental hazards and CTE mismatching\textsuperscript{a}</td>
</tr>
<tr>
<td></td>
<td>+ Provides good thermal resistance under non-vacuum conditions</td>
<td>– Degradation over time if exposed to the environment</td>
</tr>
<tr>
<td>Foam – inside</td>
<td>+ Low cost</td>
<td>– Larger structural tank wall required, resulting in increased mass</td>
</tr>
<tr>
<td></td>
<td>+ Structural wall may be not exposed to cryogenic conditions</td>
<td>– Difficult to seal from cryogenic fluid\textsuperscript{b}</td>
</tr>
<tr>
<td></td>
<td>+ Reduced CTE\textsuperscript{c} mismatch issues because of composite constituents, therefore reduced microcracking</td>
<td></td>
</tr>
<tr>
<td>Vacuum\textsuperscript{f}</td>
<td>+ Convection heat transfer suppressed or eliminated well established</td>
<td>– Heavier tank walls required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>– Costly to implement and maintain</td>
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<tr>
<td></td>
<td></td>
<td>– Loss of vacuum failure scenario</td>
</tr>
<tr>
<td>Aerogel\textsuperscript{f} (Bulk fill or blanket)</td>
<td>+ Extremely low thermal conductivity and density\textsuperscript{d}</td>
<td>– Limited mechanical properties</td>
</tr>
<tr>
<td></td>
<td>+ Provides excellent thermal resistance under non-vacuum conditions/moderate resistance under vacuum</td>
<td>– Not well established for large vessels</td>
</tr>
<tr>
<td>Perlite\textsuperscript{f} (Bulk fill)</td>
<td>+ Low cost, well established</td>
<td>– Vacuum required to achieve high performance</td>
</tr>
<tr>
<td></td>
<td>+ Low density</td>
<td>– Compaction can happen with certain tank geometries under thermal cycling and/or dynamic loads</td>
</tr>
<tr>
<td></td>
<td>+ Provides moderate thermal resistance under non-vacuum conditions/good resistance under vacuum</td>
<td></td>
</tr>
<tr>
<td>Glass Bubbles\textsuperscript{f} (Bulk fill)</td>
<td>+ Very low density</td>
<td>– Vacuum required to achieve high performance</td>
</tr>
<tr>
<td></td>
<td>+ Simplified installation due to flowability</td>
<td>– Not well established for large vessels</td>
</tr>
<tr>
<td></td>
<td>+ Provides good thermal resistance under non-vacuum conditions/excellent resistance under vacuum</td>
<td></td>
</tr>
<tr>
<td>Multilayer insulation\textsuperscript{f} (Blanket)</td>
<td>+ Low density and radiation heat transfer\textsuperscript{e}</td>
<td>– High vacuum required</td>
</tr>
<tr>
<td></td>
<td>+ Provides moderate thermal resistance under non-vacuum conditions/superior resistance under high vacuum</td>
<td>– Costly to implement and maintain</td>
</tr>
<tr>
<td></td>
<td>+ Well established</td>
<td>– Near-catastrophic failure upon loss of vacuum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>– Difficult to execute for certain tank geometries</td>
</tr>
</tbody>
</table>

\textsuperscript{a} CTE – coefficient of thermal expansion. \textsuperscript{b} Fluid infiltration leads to increased thermal conductivity, potential loss of structural wall integrity. \textsuperscript{c} These insulation methods are situated between walls. \textsuperscript{d} The balance between the structural and thermal properties can be altered and optimized for the application. \textsuperscript{e} Multilayer insulation is available in graded form to improve thermal properties and to reduce the density, but at a higher cost. \textsuperscript{f} Method must be used in conjunction with an accompanying insulation material in order to achieve proper thermal protection.
system that uses helium as the working fluid. Features of this system include zero boil-off and densified slush hydrogen production (mixture of liquid and solid hydrogen), which is detailed in Section 4.3.

4.2 Liquid hydrogen transport

In addition to selecting suitable materials for tank design, and minimising boil-off gas during transportation,\textsuperscript{92,304} another key consideration in liquid hydrogen transport is sloshing.\textsuperscript{304} This phenomenon is the movement of the liquid in the vessel due to the motion of the carrier, and it can lead to significant boil-off. Baffles may be installed in the tank to mitigate the effect.\textsuperscript{305} The LNG industry has conducted several studies into sloshing and how to minimise it,\textsuperscript{306–308} although generally it is avoided in practice by requiring minimum fill levels for vessels before they commence transport. This approach may not be sufficient for LH\textsubscript{2} transport, given the higher rate of boil-off.

To date, transportation of liquid hydrogen occurs predominantly by truck, with capacities up to approximately 60 m\textsuperscript{3} (\textasciitilde 4150 kg).\textsuperscript{271} The transportation of hydrogen by truck is primarily limited by high boil-off losses and volume capacity, rather than by weight. Safe road transport of liquid hydrogen can be achieved with existing technology; however, this is not at a scale comparable to the existing petroleum fuel distribution network.\textsuperscript{309} There exist few examples of liquid hydrogen transported by rail or aircraft.\textsuperscript{271} However these methods of LH\textsubscript{2} transportation are limited by high energy use, boil-off losses and/or total capacity.

Transporting liquid hydrogen by marine vessels has historically been limited to fuel supply for the USA and French space programs.\textsuperscript{310} In November 2016, the International Maritime Organisation provided endorsement for the transport of liquefied hydrogen in bulk by sea between Australia and Japan.\textsuperscript{311} The Hydrogen Energy Supply Chain Project (HESC), which intends to transport liquid hydrogen from the Port of Hastings in Victoria, Australia, to Kobe, Japan, will be the first commercial project to pilot liquid hydrogen maritime transport.\textsuperscript{311} The project will inform future amendments to the IGC Code (\textit{International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk}), including the potential to allow liquid hydrogen to be carried in bulk under the code without the requirement for special agreements.\textsuperscript{311}

In December 2019, Kawasaki Heavy Industries launched their liquid hydrogen tanker, designed to carry 1250 m\textsuperscript{3} of hydrogen from Australia to Japan. The liquid hydrogen vessel is cylindrical and designed with a vacuum-insulated double-walled structure.\textsuperscript{267} The support structure uses glass-fibre-reinforced plastic to minimise heat transfer.\textsuperscript{267} A boil-off rate of less than 0.4\% per day was reported, with BOG being re-stored without venting to atmosphere.\textsuperscript{267} In October 2020, Kawasaki Heavy Industries conducted a successful world-first seatrial of the liquefied hydrogen carrier SUISO FRONTIER. In December 2021, this ship departed from Japan bound for Australia. Conceptual approaches to BOG management have also investigated its use as a fuel, re-liquefying it or burning it.\textsuperscript{312}

4.3 Densification and slush hydrogen

The use of liquid hydrogen densification and slush hydrogen are prospective technological approaches for addressing the challenges of storing and transporting LH\textsubscript{2}. Reducing the temperature of liquid hydrogen to 13.8 K can increase its density by 8.8\% (77.0 kg m\textsuperscript{3}).\textsuperscript{86} Cooling further leads to the creation of slush hydrogen, a mixture of liquid and solid hydrogen at the triple point (13.8 K for \textit{para} hydrogen). The mixture can have a density up to 22\% higher than liquid hydrogen at its bubble point.\textsuperscript{86} This can offer potential reductions in size and mass of storage systems and transport vessels, and/or enable the transport of larger quantities in a given volume.\textsuperscript{297} Densification also allows for longer storage before boil-off, and increases cooling capacity when used as refrigerant.\textsuperscript{86} Traditionally, slush hydrogen has only been investigated for use in space missions.\textsuperscript{313–316} Slush hydrogen is produced via three key methods: (1) the spray method where liquid hydrogen is expanded, thus solidifying it, and mixed with liquid hydrogen; (2) the freeze–thaw method with a Dewar and vacuum pump; and (3) the Augur method (which uses helium refrigeration).\textsuperscript{317,318} The production cost of slush
hydrogen is obviously greater than the liquefaction costs of hydrogen. 319

5 LH₂ supply chains: prospects and challenges

Hydrogen has long been identified as a likely central component of future energy systems. In 1874, Jules Verne described the use of hydrogen and oxygen derived from water as fuels that would replace coal. 320 Waves of enthusiasm for hydrogen have occurred several times in the last 50 years, particularly in the 1970s and early 2000s, largely in response to concerns about energy security. However, the cost of making and using hydrogen at those times ultimately meant these waves of enthusiasm did not lead to the envisaged wide-scale use of hydrogen for energy applications.

Todays' wave of enthusiasm for hydrogen is qualitatively different to those of the last 50 years in at least three ways. It is not only motivated by energy security but also the need to decarbonise the world’s energy system. Additionally, the cost of producing renewable energy has decreased substantially, and CCS technologies are also more mature. Finally, the cost of using hydrogen to generate electricity has also dropped dramatically with the development, for example, of fuel cell technologies. These differences provide a basis for optimism regarding the current prospects for hydrogen’s ascendance to a prominent and central component of global energy supply chains.

However, if hydrogen is to meet this expectation, a number of significant challenges will need to be overcome. Within the broader context of the hydrogen value chain (Fig. 1) these challenges can generally be classified as relating to cost (e.g. $2 per kg H₂, is equivalent to $16.7 per GJ or more than 4 times the average 2021 Henry Hub natural gas price 321 ), scale (e.g. the capacity to construct or convert national-scale infrastructure for hydrogen distribution), and the maintenance of social license (e.g. managing use conflicts over scarce water resources). Challenges specific to the LH₂ supply chain may similarly be placed in one or more of the four categories identified in the introduction: economics, cryogenic losses, scale and safety. These categories are clearly inter-related with, for example, safety requirements and the magnitude of cryogenic losses associated with liquid hydrogen storage inherently impacting its economics. Section 4 considered the underlying issues and emerging technical solutions relating to cryogenic losses of LH₂. This section reviews the challenges and prospects associated with the other categories, by first covering the safety of liquid hydrogen supply chains and then considering their economics and scale-up. Comparisons with liquid ammonia, the primary alternative hydrogen vector to LH₂, are then reviewed before a summary is presented of the priority research and development areas needed to advance liquid hydrogen supply chains.

5.1 Safety of liquid hydrogen supply chains

Ensuring the safe operation of hydrogen value chains is a challenge that relates to both cost and the maintenance of social licence. General awareness of the Hindenburg disaster after more than 80 years is a stark example of how easily energy technologies can be substantially tarnished in the mind of the public, even if the accident’s root cause had little to do with hydrogen per se. 322 The development and application of effective and efficient engineering standards are the central tool to address the challenge of hydrogen safety.

There are several factors that give rise to safety risks inherent to the hydrogen value chain in general and liquid hydrogen in particular. Hydrogen gas has a strong propensity to leak due to its small molecular size and high diffusivity. A number of NASA launches have been halted due to hydrogen leaks, mostly in umbilicals. 86 Hydrogen can also cause embrittlement of many materials, resulting in cracking and catastrophic failure of metals significantly below the yield stress. Furthermore, hydrogen has a high propensity to ignite due to its wide flammability range (4 to 74 vol% in air) and very low ignition energy (0.017 mJ). 321 It has been shown to spontaneously ignite on sudden release from pressurised containers, although the mechanism is not fully understood. 323 Hydrogen flames burn with a hot but near-invisible flame, making them difficult to detect. 324

For systems producing or handling liquid hydrogen, the materials of construction must be both resistant to hydrogen embrittlement and suitable for use at cryogenic temperatures. Consideration must also be given to the expansion and contraction caused by the changes from ambient to liquid hydrogen temperatures. 323 Liquid hydrogen can cause other gases (such as air and nitrogen) to condense and solidify – this can cause blockages and failures in equipment. As a result, storage tanks should be kept under positive pressure to prevent air ingress and purges of equipment should be followed by refilling with hydrogen, or replacement with helium. 323

Liquid hydrogen and the associated boil-off gas can produce severe burns upon contact with the skin and delicate human tissue such as the eyes. 323 Until the hydrogen vapourises as it warms, it will accumulate as a substance denser than air. This produces a considerable fire and explosion risk. This has resulted in vent line explosions in the past. 86 In the situation that liquid hydrogen comes into contact with another liquid at a temperature above hydrogen’s boiling point, there is a risk of a rapid phase transition explosion. 323 This phenomenon has been observed for spills of LNG on water, but is not well understood for liquid hydrogen. 323

NASA has observed significant degradation in performance of cryogenic hydrogen storage tanks due to issues with insulation systems. 86 For example, a perlite void resulted in the venting of over 12,000 gallons per day of hydrogen. 86 It was unclear what may have caused the void to form. Vacuum leaks have also posed a significant problem as evidenced by increased boil-off. These leaks resulted in the solidification of air in the storage tank annulus, which subsequently liquefied (as LH₂ was removed from the tank) and cooled the vacuum jacket. 86 This phenomenon decreased the tank wall temperature below its ductility limits, thereby cracking the vacuum jacket; 86 it could have been prevented by draining the tank more slowly whilst heating the outer vessel with water. 86
PRESLHY\textsuperscript{324} is currently conducting experimental work in hydrogen release and mixing, ignition, and combustion with a view to providing enhanced recommendations for safe design and operations of liquid hydrogen technologies.\textsuperscript{324–326} Kawasaki Heavy Industries in collaboration with TEN, JAXA, JARI, and the University of Tokyo have conducted experiments into the safety of liquid hydrogen storage including diffusion behaviour and heat leaks through cryogenic tank supporting structures.\textsuperscript{267} These tests will help inform the development and strengthening of engineering standards that further increase the safety of planned LH\textsubscript{2} supply chains.

**International standards for liquid hydrogen and maritime regulation.** International hydrogen standards already exist and continue to be developed\textsuperscript{127} both by the International Organisation for Standardization (ISO) and the International Electro-technical Commission (IEC). A number of international technical committees now are responsible for drafting standards in specific fields.\textsuperscript{328} Relevant standards for hydrogen liquefaction and storage include ISO/TC:223\textsuperscript{329} (road vehicles), ISO/TC 197\textsuperscript{330} (hydrogen technologies), and IEC/TC 105\textsuperscript{331} (fuel cell technology).

Most hydrogen-specific transport and storage standards are, however, still in development and targeted primarily at the utilisation stage of the value chain. Long-standing LNG and Liquefied Petroleum Gas (LPG) storage and transport standards may have the potential to cover relevant areas for the export of liquid hydrogen; however, this will require considerable review.\textsuperscript{322,333} Whilst the behaviour of LNG and LPG during transport is well understood, liquid hydrogen presents a unique set of challenges, particularly in the understanding of stratification, sloshing, boil-off gas, and pressure build-up. The National Fire Protection Association (NFPA) released a safety code which provides fundamental safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas (GH\textsubscript{2}) form or cryogenic liquid (LH\textsubscript{2}) form.\textsuperscript{334}

Standards that govern the handling of liquid hydrogen at the point of use include ISO 13984 (Liquid hydrogen – land vehicle fuelling system interface) and ISO 13985 (Liquid hydrogen – land vehicle fuel tanks).\textsuperscript{329} Standards that govern safety regarding liquid hydrogen and associated infrastructure include ISO/TR 15916 (Basic considerations for the safety of hydrogen systems), ISO 26142 (Hydrogen detection apparatus – stationary applications), and IEC EN 60079-10, 14, 17, and 19 (Electrical apparatus for explosive gas atmospheres: classification of hazardous areas, inspection and maintenance, and repair). There are also eleven ISO standards for materials testing, six of which cover hydrogen embrittlement.\textsuperscript{325} Specific guidelines and recommendations have been developed by projects funded through the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) (a public-private partnership) including\textsuperscript{136} HYPER, HyApproval, HyIndoor, HyFacts, HyResponse and HySEA. The transport of liquefied gases by sea is covered by the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code),\textsuperscript{337} which is a mandatory code under The International Convention for the Safety of Life at Sea (SOLAS Convention). The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC code) does not currently allow for the transportation of liquid hydrogen.\textsuperscript{311}

The current state of standards thus requires first movers to negotiate regulation and permit requirements that are unclear, or not yet adapted for hydrogen use. Risk analysis toolkits, such as HyRAM,\textsuperscript{338} have the potential to enable industry and standard development organisations to take a performance-based engineering approach to regulation.

While the development of standards will help with addressing this safety challenge, a gap in the general public’s understanding of hydrogen has been identified.\textsuperscript{339} Over fifty articles have studied public perceptions of hydrogen across a broad range of applications.\textsuperscript{339} Currently, liquid hydrogen is not prominent in the public perception as it is mainly used in industrial applications. However, emerging applications such as its storage and use in domestic refuelling stations, may change this, particularly if an incident occurs where public safety is put at risk.

Several publications studying perceptions of hydrogen have found that public attitudes appear to be generally neutral.\textsuperscript{339–345} These studies found that the most frequently identified concerns with the use of hydrogen technologies were safety and cost.\textsuperscript{339} A majority of participants identified that they would only be willing to pay for the use of hydrogen technologies if the costs were comparable or less than those of conventional technologies, even if there were clear environmental benefits.\textsuperscript{339} Thus even once the challenge of safety has been adequately addressed, the growth prospects for liquid hydrogen supply chains will be acutely dependent on how well the challenges of economics and scale can be addressed.

### 5.2 Cost and scale-up of liquid hydrogen supply chains

Projections of annual global hydrogen demand in 2050 have reached as high as 621 million tonnes.\textsuperscript{129} Near term growth in the liquid hydrogen market is projected to be 5.66\% annually in the five years to 2024.\textsuperscript{346} For demand to reach these levels, the levelised cost of hydrogen (LCOH) associated with the entire value chain will need to decrease. Most analyses of the pathways by which this cost reduction can be achieved focus on scale up of the process to meet the larger demand. Fig. 17 and Table 9 present a summary of literature studies which have analysed the LCOH of possible liquid hydrogen supply chains, with scales ranging from (27 to 16 400) tonnes per day: the world’s current largest single liquefier has a capacity of 32 TPD.

Fig. 17 shows how the LCOH of the liquid hydrogen supply chain was split by each study across four cost components: production, liquefaction, transport and distribution. The scale of the supply chain and the electricity cost assumed for the liquefaction process are also indicated. It is clear that there is significant variation between studies in the contribution of each cost component to the overall LCOH, which can make it difficult to compare different analyses or identify any trends associated with scale. The most variable component across the literature studies is the distribution cost, which ranges from 0 for several studies where it was not considered at all to
8.2 US$ per kg\textsubscript{H\textsubscript{2}}. This extreme latter value comes from a 2019 study reported by the DOE\textsuperscript{109} where the distribution cost included the construction of 79 refuelling stations, each dispensing 350 kg day\textsuperscript{-1}, as well as other costs such as taxes, insurance, licensing and permits. Reuß \textit{et al.}\textsuperscript{108} have observed that the significant variation of costs for different refuelling stations is caused by site location, station design and capacity. Li \textit{et al.}\textsuperscript{97} assessed the cost of various station designs, sizes and configurations. Large-scale hydrogen refuelling stations with a supply capacity of 1000 kg day\textsuperscript{-1} or more have distribution costs in the range (0.9 to 2.3) US$ per kg\textsubscript{H\textsubscript{2}}.

The second most variable component in the LCOH of prospective LH\textsubscript{2} supply chains considered in the literature is the production cost. The comparisons shown in Fig. 17 indicate whether blue or green hydrogen production was assumed; in several studies two different LCOH values were reported with the only difference being the method of production. For example, the APERC\textsuperscript{347} conducted a study to calculate the total cost of hydrogen provision in Japan in 2030. Japan has set a target landed price of 3.3 US$ per kg\textsubscript{H\textsubscript{2}} by 2030 and a longer term target of 2.2 US$ per kg\textsubscript{H\textsubscript{2}}\textsuperscript{348}. The study considered different international scenarios with an estimated hydrogen production cost from fossil fuel coupled with carbon capture and storage up to 2.8 US$ per kg\textsubscript{H\textsubscript{2}}, and from renewable energy up to 6.6 US$ per kg\textsubscript{H\textsubscript{2}}\textsuperscript{94}. The study compared the cost for the liquid hydrogen supply chain in Japan with conventional fuels used directly for electricity generation or in refuelling stations for fuelling FCVs. The APERC study estimated an imported (delivery) cost between (2.5 and 6.8) US$ per kg\textsubscript{H\textsubscript{2}} when used for power generation and a total dispensing cost between (4.5 and 13) US$ per kg\textsubscript{H\textsubscript{2}} when used in refuelling stations\textsuperscript{94}. This study concluded that imported hydrogen produced from fossil fuels with CCS can be competitive with power generation from oil by 2030 and with the cost of petrol in Japan if large capacity refuelling stations are utilised.

More recently, Longden \textit{et al.}\textsuperscript{349} compared the costs and carbon emissions associated with different modes of hydrogen production. Distributions of costs were collated from 97 estimates across 16 studies that considered both green and blue hydrogen production technologies with various levels of carbon capture and storage. They reported a median cost of hydrogen production from renewables of 3.64 US$ per kg\textsubscript{H\textsubscript{2}}, with a range from (2.13 to 7.79) US$ per kg\textsubscript{H\textsubscript{2}}, resulting from the assumed capital cost ($500–2500 per kW), renewable electricity price ($10 to $85 per MW h) and/or electrolyser capacity factor (26 to 48%).

The median cost of hydrogen produced by natural gas SMR with at least 90% CCS was 2.09 US$ per kg\textsubscript{H\textsubscript{2}}, with a range from (1.21 to 2.93) US$ per kg\textsubscript{H\textsubscript{2}}. At this level of CCS, the emissions intensity of using the blue hydrogen as a fuel was estimated to be about 22 kg\textsubscript{CO\textsubscript{2}-equiv} GJ\textsuperscript{-1}, which is about one third that of using the natural gas directly.

The liquefaction and transport cost components have comparatively smaller variances than those of production and distribution and, based on the averages across the studies considered in Table 9, are the third and fourth largest contributors to the LCOH of the liquid hydrogen supply chains, respectively. The liquefaction cost
cost component has an average of (1.45 ± 0.66) US$ per kgH₂, where the error bound denotes the standard deviation for the studies listed. The transport cost component of the liquid hydrogen supply chains varies slightly more, depending on the distance considered by the supply chain with an average of (1.32 ± 0.71) US$ per kgH₂ across all studies. Supply chains that involve maritime transport over distances of 1000 km or more had average transport costs of 0.14 US$ per kgH₂ per 1000 km, while over shorter distances (80 to 500 km) transport costs increased to 4.78 US$ per kgH₂ per 1000 km.

Liquefaction costs for the various studies depended on both the energy (electricity) price assumed and the scale of the process. Fig. 18 shows the estimated liquefaction cost component for each study in Table 9 against the scale of the LH₂ supply chains. The scales considered cover a range from just below the largest current LH₂ train in operation to conceptual trains 1000-times as large, with capacities similar to current mega-scale LNG trains. While there is considerable scatter in the estimated liquefaction costs, increasing the supply chain capacity above 100 TPD is expected to bring this component of the LCOH down to around 1 US$ per kgH₂.

At this stage, it is unclear whether increasing the scale of LH₂ production trains beyond 100 TPD would lead to further reductions in unit liquefaction costs. It may be that the modularisation of unit operations at a standard size can help lower manufacturing costs by more than the economy of scale benefits that might be achieved in single trains with larger capacities. In either case, up-scaling the equipment required for larger capacity liquefaction trains presents specific technical challenges as discussed in Sections 3 and 4. These include equipment size, process efficiency, cost, safety, boil-off losses and management and insulation methods for large scale storage tanks.

A reduction in liquefaction cost to around 1 US$ per kgH₂ or below will nevertheless be essential to the establishment of economically viable, wide-spread liquid hydrogen supply chains. Together with the anticipated reductions in the cost of producing clean hydrogen to 2 US$ per kgH₂ or below, this should enable liquid hydrogen supply chains that service fuel cell vehicle (FCV) refuelling networks even with relatively high distribution costs. For example, a report published by the California Energy Commission, estimated the LCOH of hydrogen produced from renewables and used for FCVs in California will decline from around 16 US$ per kgH₂ to as little as 5.3 US$ per kgH₂ in 2050, which is close to the 4 US$ per kgH₂ long-term target established by the U.S. Department of Energy.

5.3 Comparison with ammonia

Ammonia is an alternative carrier to liquid hydrogen for storage and transport applications, which in contrast already has international supply chains established. To provide context for the above discussion of prospective liquid hydrogen supply chains, this section considers the use of ammonia as a transport vector in terms of energy consumption, cost and emissions.

Using the conventional Haber Bosch (HB) process, the production of ammonia from H₂ and N₂ consumes power in the range of (2–4) kWh kgNH₃⁻¹. However, as indicated in Table 2, on a hydrogen mass basis this is equivalent to (11.2–22.5) kWh kgH₂⁻¹, which is comparable to or larger than the SEC currently required for hydrogen liquefaction of (11.9–15) kWh kgH₂⁻¹. The primary advantage of ammonia relative to liquid hydrogen is its ease of storage and transport with minimal loss. However, if at the point of end use ammonia must be converted back to H₂ (e.g. prior to use in a fuel cell), a further 7.94 kWh kgH₂⁻¹ must be used assuming a cracker efficiency of 76% in the best case scenario. In such cases the storage and transport advantages of using NH₃ are greatly ameliorated, with between (57.4 and 90.4)% of the hydrogen stored in the vector being consumed to produce the necessary energy for conversion and (re-)cracking.

Instead of cracking, it is possible to use ammonia as an energy carrier by direct combustion (engine or gas turbine) or, potentially, in fuel cells. The latter technology is still pre-commercial, while the former must deal with challenges such as unwanted NOₓ emissions, CO₂ tolerance and the relatively low flammability of ammonia. These challenges have to some extent been addressed through research and development with some demonstration-scale (10–40 kW) turbines and engines. Nevertheless, further research, development and up-scaling is required for these technologies given that the climate impact of ammonia combustion by-products can be multiple times worse than those of CO₂.

While ammonia production, storage and transport are very mature technologies, the associated costs are still important considerations when assessing its use for energy applications (as opposed e.g. to food production). Location and plant capacity are two factors influencing ammonia production cost, which range from 0.21–0.40 US$ per kgNH₃ in Western Europe to as little as 0.14 US$ per kgNH₃ on the US Gulf Coast. This is collectively equivalent to around (0.8–2.2) US$ per kgH₂ considering the content of hydrogen in 1 kg of ammonia. Decomposition back to H₂ adds approximately 0.67 US$ per kgH₂ giving a total cost of (1.5–2.9) US$ for each kg of hydrogen transported as NH₃. This is comparable with the sum of the liquefaction and transport costs averaged across all the LH₂ studies considered in Table 9 (2.8 ± 0.7) US$ per kgH₂.

Finally the widespread use of ammonia for energy applications has safety challenges potentially comparable to those faced by liquid hydrogen. These include increased rates of corrosion and material wear for containers storing both gaseous and liquid ammonia; high toxicity to biological systems and ammonia’s capacity to rapidly dehydrate living tissue; its propensity to form secondary fine (< 2.5 µm) particulate matter upon combustion; and disruption of natural nitrogen deposition cycles. Thus while industry has an established track record of safely storing and transporting NH₃ at commercial scales, significant handling and containment challenges remain if it is to be used on an even larger scale for energy applications.
Table 9: Liquid hydrogen value chains reported in literature ordered by increasing amount of liquefaction cost

<table>
<thead>
<tr>
<th>Study/report</th>
<th>Scale</th>
<th>H2 Production</th>
<th>Liquefaction</th>
<th>Transport</th>
<th>Distribution</th>
<th>Total cost [$/kg H2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>APERC (^a)</td>
<td>800</td>
<td>2.15–4.13 (^d)</td>
<td>1.22–2.44 (^f)</td>
<td>1.07–1.23</td>
<td>0.46</td>
<td>2.75–3.56 (^h)</td>
</tr>
<tr>
<td>Heuser (^d)</td>
<td>95</td>
<td>50</td>
<td>2.86</td>
<td>1.47</td>
<td>0.24–1.65</td>
<td>5.43–6.85 (^k)</td>
</tr>
<tr>
<td>Wijayanta (^k)</td>
<td>9500–10 300</td>
<td>2.76–3.56 (^a)</td>
<td>1.07–1.30</td>
<td>0.74</td>
<td>3.80–4.64 (^f)</td>
<td></td>
</tr>
<tr>
<td>KHI (^b)</td>
<td>100</td>
<td>1.55</td>
<td>1.18</td>
<td>1.47</td>
<td>0.24–1.65</td>
<td>5.43–6.85 (^k)</td>
</tr>
<tr>
<td>CSIRO37 (^c)</td>
<td>50</td>
<td>1.13–2.08 (^g)</td>
<td>2.36</td>
<td>1.53–2.10</td>
<td>0.28–1.68 (^f)</td>
<td>5.43–6.85 (^k)</td>
</tr>
<tr>
<td>REUSS (^e)</td>
<td>50</td>
<td>3.10–4.90 (^h)</td>
<td>1.13–2.10</td>
<td>1.52–2.10</td>
<td>0.28–1.68 (^f)</td>
<td>5.43–6.85 (^k)</td>
</tr>
<tr>
<td>DOC (^f)</td>
<td>27</td>
<td>2.28–2.64 (^f)</td>
<td>2.75</td>
<td>1.25–2.20</td>
<td>0.15–1.74</td>
<td>4.31–5.96 (^k)</td>
</tr>
<tr>
<td>European Commission</td>
<td>27</td>
<td>1.15–14.07 (^j)</td>
<td>2.76</td>
<td>2.28–2.64 (^f)</td>
<td>2.28–2.64 (^f)</td>
<td>4.31–5.96 (^k)</td>
</tr>
</tbody>
</table>

**Notes:**
- \(^a\) Includes the levelized cost of compressing and transporting hydrogen via electrolysis powered by wind.
- \(^b\) Includes the cost of storing LH2 before shipping, based on a maritime route from Patagonia to Japan.
- \(^c\) Includes the cost of storing LH2 before shipping, based on a land route to Japan.
- \(^d\) Cost calculated for a truck that travels 166 330 km per annum as per IDEALHY104–106.
- \(^e\) Cost calculated with an interest rate of 0.5 and 5%, respectively.
- \(^f\) Includes distribution costs, according to data available in the literature.
- \(^g\) Includes the cost of refuelling for a 100 km round trip transported by road.
- \(^h\) Includes the cost of regasification only (in Japan).
- \(^i\) Includes buffer storage costs.
- \(^j\) Average exchange rate over the last 6 months: 0.67 USD = 1 AUD, 1.12 USD = 1 EUR, 1 USD = 107.2 JPY.
- \(^k\) Includes the cost of regasification and carbon capture.
- \(^l\) Includes the cost of shipping hydrogen via a truck that travels 166 330 km per annum.
- \(^m\) Includes the cost of producing hydrogen through steam reforming via electrolysis powered by wind.
- \(^n\) Includes the cost of producing hydrogen through coal gasification and CCS.
- \(^o\) Includes the levelized cost of hydrogen produced through electrolysis via power purchase agreements.
- \(^p\) Includes the cost of producing hydrogen through coal gasification and CCS.
- \(^q\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^r\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^s\) Includes the cost of producing hydrogen through coal gasification and CCS.
- \(^t\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^u\) Includes the cost of producing hydrogen through coal gasification and CCS.
- \(^v\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^w\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^x\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^y\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^z\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^aa\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ab\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ac\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ad\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ae\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^af\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ag\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ah\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ai\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^aj\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ak\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^al\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^am\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^an\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ao\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ap\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^aq\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ar\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^as\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^at\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^au\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^av\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^aw\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ax\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ay\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^az\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^ba\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bb\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bc\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bd\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^be\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bf\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bg\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bh\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bi\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bj\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bk\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bl\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bm\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bn\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bo\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bp\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bq\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^br\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bs\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bt\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bu\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bv\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bw\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bx\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^by\) Includes the cost of producing hydrogen through steam reforming and CCS.
- \(^bz\) Includes the cost of producing hydrogen through steam reforming and CCS.
Wijayanta et al.98 predicted an imported cost, including hydrogen production from SMR, of ammonia from Australia to Japan by 2030 of around 0.44 US$ per kg_NH₃ (2.5 US$ per kg_H₂) if ammonia can be used directly, and a total cost of 0.563 US$ per kg_NH₃ (3.2 US$ per kg_H₂) when ammonia is decomposed back to hydrogen. They concluded that when highly pure H₂ is needed (such as for fuel cell vehicles), liquid hydrogen is more promising than ammonia and other hydrogen storage methods. Ishimoto et al.360 conducted a hydrogen export value chain analysis over distances ranging from (2500 to 23,407) km for both LH₂ and ammonia. The hydrogen was produced by Autothermal Reforming at the same location for both vectors and the ammonia was cracked back to H₂ at the destination. Using conservative costs for currently available technologies, Ishimoto et al.360 found that the LH₂ supply chain costs ranged from (4.8 to 6.8 US$ per kg_H₂), which were generally below those of NH₃ (6.1 to 6.6 US$ per kg_H₂), except for the longest distance supply chain. Moreover, the carbon emissions intensity of the LH₂ supply chains were (5 to 7.2) times lower than those using NH₃. Similarly, an analysis by the EU Science Hub – Joint Research Centre361 found that LH₂ resulted in lower hydrogen delivery cost than NH₃ for supply chain distances up to 22,000 km. Their analysis found that LH₂ also had a supply chain cost below that of either pipelines or liquid organic hydrogen carriers for distances between (3000 and 17,000) km.

5.4 Research, development & demonstration priorities for liquid hydrogen supply chains

The ammonia comparison helps illustrate that liquid hydrogen supply chains have reasonably good prospects relative to (and in conjunction with) those based on alternative vectors. However, practical solutions to multiple challenges in the four categories of economics, cryogenic losses, safety and scale presented in this paper will be required if large-scale LH₂ supply chains are to be established. To address this array of challenges, significant levels of research, development and demonstration will be needed. Table 10 presents a summary of these needs, with a brief discussion of each of the main categories – liquefaction, storage & transport, and

Fundamentals – given in the text below. The areas and topics listed in Table 10 are based on the literature review presented in this paper and discussions with industry-based subject matter experts, which provided guidance on prioritisation. Accordingly, the list is non-exhaustive; rather it reflects an informed, yet subjective perspective of technical and engineering needs based on current knowledge.

Liquefaction: increase efficiency & lower cost by scale-up.

Significant work needs to be done to reduce the specific energy consumption (SEC) of hydrogen liquefaction to well below 10 kWh kg⁻¹H₂ and improve its exergy efficiency. Exploiting economies of scale will be central to achieving this improved energy efficiency while also reducing the specific liquefaction cost (SLC). Particular areas that should be prioritised for research, development and demonstration include:

- The design and fabrication of larger coldboxes (e.g. on site), or the viability of hosting cryogenic equipment (e.g. heat exchangers) in multiple smaller coldboxes. Work on optimal modular arrangements of coldboxes to insulate different parts of the system while keeping capital costs down is also needed.
- The design of large oil-free turbines for H₂ expansion and the use of turbo-compressors on the working-fluid side of the liquefaction process needs further research regarding their suitability for use in large-scale operations. Owing to the difficulties in compressing hydrogen, research into heavier compressing gases (e.g. MRs) used in the pre-cooling and refrigeration cycles should accompany this work. Additionally, the potential of using the electrochemical compression of hydrogen for large-scale operations should be explored given its established high efficiencies (95% for Carnot cycle up to 1 MPa).362,363
- Robust optimisation of large-scale liquefaction processes based on Brayton cycles through the use of new mixed-refrigerants, pre-cooling stages, process integration, efficient catalysts, and pressure drop reductions across and between unit operations. Such an optimisation will require robust, accurate and computationally efficient simulation platform for > 100 TPD LH₂ plant capable of describing several inherently dynamic (non-steady state) processes in a variety of configurations. Such simulations should use reference thermodynamic and transport properties models for hydrogen and mixed refrigerants, and an accurate kinetic model for ortho-para conversion, as recommended in the Fundamentals priority list below.
- The design of improved ortho- to para-hydrogen conversion reactors that optimise the rate of conversion and heat removal (and hence the management of potential heat spots) as well as the pressure drop experienced by the hydrogen during continuous operation. Currently, the amount of catalyst required for a given flowrate or quantity is specified based on proprietary kinetic data. The development of new catalysts that are easier to integrate into heat exchanger designs and/or work efficiently with trace removal systems (adsorbers) could help reduce both the capital cost (e.g. lower equipment counts) or operational cost (pressure drop) of liquefaction processes. The integration of new catalyst materials into vortex tube heat exchangers and/or the development of catalytic coatings are
### Table 10: Suggested research, development and demonstration priorities for the liquid hydrogen supply chain

<table>
<thead>
<tr>
<th>Area</th>
<th>Sub area</th>
<th>R&amp;D opportunities</th>
<th>Potential impact</th>
</tr>
</thead>
</table>
| Liquefaction          | Process design                | • Cold box modularity and system integration  
• Liquefier capacity and arrangement optimisation  
  [e.g. 10 × 10 TPD vs. 1 × 100 TPD]  
• Optimisation of MR/fluids and pre-cooling fluids  
  [techno-economic & environmental]  
• Large-scale Brayton cycles optimised with robust, accurate  
  dynamic process simulations  
• Investigate use of electric-drive compressors powered by  
  variable renewable energy profiles  | • Enable construction of >100 TPD liquefiers with SEC between (6 and 8) kUSD kgH₂⁻¹ vs. 100 TPD liquefiers  
  [1]  
• Improved heat exchanger designs with integrated catalysts  
  for OP conversion.  
• Large-scale oil-free turbines and/or large, economical  
  electrochemical compressors for H₂  
• Construction with hydrogen-proof materials and effective  
  cryogenic seals to prevent leakage  
• Optimise trace impurity removal processes (e.g. integration  
  with OP conversion process)  
• Robust sensors for monitoring blockage risk in cryogenic  
  heat exchangers  | • Increased equipment efficiency and suitability for large-scale liquefiers, thus enabling construction of >100 TPD liquefiers  
  [1]  
• Improved operational efficiency with reduced design margin requirements  |
|                       | Equipment design              | • New OP catalysts with improved efficiencies, characterised over wide temperature range  
• Catalyst performance (kinetics, heat & mass transfer) within  
  dynamic process simulations  
• Develop catalytic coatings & incorporate catalysts into novel  
  heat exchangers (vortex tubes)  
• Robust sensors for monitoring OP ratio in process streams  
  over wide temperature range  | • Reduced pressure drop in the heat exchangers  
• Cheaper and/or more efficient heat exchangers  
• Better monitoring of OP conversion performance allowing real time  
  optimisation  | |
| Storage & transport   | Tank design & operation       | • Vacuum panels, surface coatings, tank wall channels, 3D printed tanks for better insulation  
• Convert from spherical to cylindrical or conformal tank designs  
• Efficiently integrate cryo-compressed and slush H₂ storage  
  technologies  
• Address deficiencies & exploit strengths of existing  
  insulation materials & methods [see Table 8]  
• Better models for predicting thermal stratification,  
  interfacing heat transfer & resulting boil-off  | • Safer storage with reduced boil-off losses  
• Enable construction of large-scale storage tanks for more cost-effective transport  
  [1]  
• Improve storage capacity of LH₂  | |
|                       | Shipping & custody transfer   | • Leak-free umbilicals and disconnects with good thermal insulations  
• Improved design & operability of cryogenic hoses, venting  
  systems and flow meters  
• Design large storage tanks with wide ranges of operating  
  pressure to accommodate boil-off  
• Optimise ship ballast & sloshing protection requirements to  
  account for low density cargo  
• Develop operational procedures to keep empty ship tanks  
  cool (or minimise cool-down time)  | • Improve safety and minimize boil-off losses  
• Reliable & safe export infrastructure  
• Minimise energy wasted during transfer operations  | |
| Safety                |                               | • Develop standards for leak-free operations & avoiding material compatibility problems  
• Leak detection systems with appropriate spatial extent &  
  temporal resolution  
• Improve detection and develop procedures for stopping  
  “invisible” fires  
• Long-term cyclic (thermal, pressure) testing of materials &  
  systems in LH₂ supply chain  | • minimise risk of containment failures  
• Reduce risk of hydrogen fires or explosions  
• Provide pathways for safe workforce expansion and public utilisation  | |
| Fundamentals          | Fluids                        | • EOS [1] based on new (enthalpy) data for fluid mixtures containing H₂ with varying OP ratios  
• EOS based on new (enthalpy) data for cryogenic MR fluids  
• Data & models for predicting solubilities, freeze-out kinetics &  
  deposition risk of impurities in H₂  
• Data & models for predicting impurity solubility, freeze-out &  
  deposition risk in refrigerants  
• Improved data & models for transport properties of  
  cryogenic hydrogen & MR fluids  | • Helps with liquefaction opportunities listed above for process design and equipment design categories  
• Helps with storage & transport opportunities listed above for tank design and operation category  |
promising avenues for further research. Realising any of these opportunities would require a thorough quantification of reaction kinetics (Fundamentals) and their efficient inclusion into reactor models and process simulations recommended above. The development of efficient, standard approaches for the by-line or on-line measurement of para-hydrogen content would facilitate the validation of these conversion technologies as well as the real-time optimisation of plant operation.

Storage and transport: reduce cryogenic losses & ensure safety. Boil-off losses associated with the storage, transportation and handling of liquid hydrogen can consume up to 40% of its available combustion energy.\(^8\) Accurate assessment of pressurisation dynamics, thermal stratification and boil-off rates are critical for the design and operation of transfer lines and storage tanks that minimise both LH\(_2\) losses and hazards to safety. Specific areas for research, development and demonstration that will make LH\(_2\) storage and transport more efficient and less risky include:

- Demonstrate innovative insulation schemes and materials to minimise boil-off losses for future large-scale storage tanks and transfer pipelines. As detailed in Table 8, each existing method of insulation has strengths and weaknesses; mechanisms for overcoming the latter and exploiting the former should be investigated, potentially through combinations of different techniques and materials.
- Develop a comprehensive dynamic model able to reliably estimate boil-off rates, thermal stratification, pressurisation and flow dynamics, across a wide range of tank geometries and scales, both during static storage and custody transfer (loading) operations. This model should be validated against data acquired using a range of facilities with instrumentation sufficient to capture the underlying relevant multi-scale phenomena. The ability to describe the impact of sloshing, (auto) ortho-para conversion, superheated vapour phases with non-equilibrium ortho-para ratios, and boil-off return and re-liquefaction facilities will be important features of such a dynamic model.
- Explore the use of slush hydrogen technologies to simultaneously reduce boil-off rates and increase volumetric energy density. While implementing the additional refrigeration systems required will increase both capital and operational costs, these may be sufficiently offset by efficiencies achieved through system integration and economies of scale.
- Avoiding hydrogen leaks is one of the most difficult but important challenges that must be overcome to ensure sustained safe operations. While the development of standards and operational practice will help mitigate risks associated with de-pressurisation, fire and explosion, technologies that help eliminate and/or correct for human error will be just as important. Intelligent, automated and high-resolution systems for detecting and suppressing leaks or fires across a range of environments (liquefaction plants, ships, domestic fuelling stations) are needed. Additionally, innovations that are potentially “low-tech” in comparison, such as leak-free, hydrogen compatible connectors for cryogenic hoses will likely be of significant value.

Fundamentals: improved descriptions of fluids & catalysts. While the underlying science and basic engineering requirements for hydrogen liquefaction are known, significant limitations exist regarding the quantification of key properties needed for improved technical solutions. To progress many of the research and development priorities listed under Liquefaction or Storage & Transport, improved quantitative descriptions of the fluids, catalysts and other key materials used in liquefaction are needed over a wide range of conditions. While much of the basic data required for hydrogen liquefaction processes were obtained over 50 years ago to facilitate the development of rockets and space programs, process efficiency was a relatively low priority compared with the large-scale energy-driven applications now planned.

To reduce the engineering margins applied within LH\(_2\) supply chains, smaller uncertainties are needed in the models used for process design. This provides a motivation to re-visit and extend the underlying database of thermodynamic and kinetic properties. Moreover, measurement technology has

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### Table 10 (continued)

<table>
<thead>
<tr>
<th>Area Sub area</th>
<th>R&amp;D opportunities</th>
<th>Potential impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalysts &amp; materials</td>
<td>- Cheaper catalysts with reaction kinetics including heat &amp; mass transfer limitations characterised (e.g. particle size effects) over wide ranges of temperature, pressure and initial OP ratio. - Cryogenic adsorption capacities &amp; kinetics of media used for trace impurity removal - High-strength, low cost containment materials compatible with H(_2) &amp; cryogenic temperatures - Improved thermal insulation materials with long lifetimes &amp; tolerance for cycling.</td>
<td>- Helps with liquefaction opportunities listed above for equipment design and OP conversion categories</td>
</tr>
<tr>
<td>Sensors</td>
<td>- Robust by-line or on-line measurements of OP ratio capable of operating in live plant - Robust by-line or on-line measurements of impurity freeze-out or deposition risk - Effective sensors for hydrogen leaks and/or fires with flexible spatial &amp; temporal resolutions</td>
<td>- Helps with liquefaction opportunities listed above for equipment design and OP conversion categories - Helps with storage &amp; transport opportunities listed above for safety category</td>
</tr>
</tbody>
</table>

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advanced significantly since a large fraction of the original data were acquired. Developing and applying new experimental techniques to reduce the uncertainty and extend the range of property data, both in the laboratory and in the plant via new sensors, will assist the establishment of more efficient, large-scale liquid hydrogen supply chains. Research priorities within the Fundamentals category include:

- Thermophysical property data for hydrogen and its mixtures are needed at temperatures from 20 K to 300 K and pressures from ambient to 8 MPa. As detailed in Section 2, a relatively large body of experimental data exists for the density, thermal conductivity and viscosity of hydrogen. However, their coverage of the conditions relevant to liquefaction are in some cases inadequate, and many of the data sets have significant scatter with few of the original articles providing a sufficiently detailed uncertainty analysis. New data should cover wider ranges of ortho–para ratios, particularly in the supercritical region (30 K to 100 K); however, it is essential that the ortho–para ratio for each data point be measured or well-defined. Importantly, data that provide more direct information about the fluid mixture’s enthalpy (e.g. heat capacities, sound speeds, vaporisation) would enable significant improvements upon the Helmholtz EOS of Beckmüller et al.\textsuperscript{154} which only considers normal hydrogen. These more accurate and wider-ranging thermophysical property data would then enable correspondingly improved reference Helmholtz equations of state and transport property models for hydrogen mixtures that are central to process simulations.

- Similarly, new thermophysical property data and improved models are needed for a range of prospective mixed refrigerant fluids likely to be central to the development of hydrogen liquefaction cycles with SECs in the range (6 and 8) kWh kg\textsubscript{H\textsubscript{2}}\textsuperscript{−1}. Given their prospective use in both the pre-cooling and cryogenic sections of the plant, there are many mixtures that could help improve overall cycle efficiency (e.g. methane + iso-pentane at temperatures as low as 98 K\textsuperscript{164}). Again, measurements that provide information about the fluid mixture’s enthalpy as a function (T,p) and composition would be of significant value to refrigerant design.

- A more universal kinetic expression for catalyst assisted ortho–para hydrogen conversion is required. Fundamental experiments that characterise reaction kinetics, including particle size effects and other heat and mass transfer limitations, over wide ranges of temperature, pressure and initial ortho–para ratio will be necessary to validate such an expression. Data on the reverse reaction rate should also be acquired, and a wider range of catalyst materials and morphologies should be investigated to identify potential methods of reducing the cost of conversion. Techniques for accurately and rapidly monitoring ortho–para ratios developed for the laboratory should be considered as the basis for improved sensor technologies that can operate in liquefaction plant environments.

- At the cryogenic temperatures encountered in hydrogen liquefaction plants, trace concentrations of impurities can freeze-out and lead to heat exchanger blockages and even plant shutdowns. This risk is similar to that present in the liquefaction of natural gas\textsuperscript{365–370} where the concentrations of H\textsubscript{2}O, C\textsubscript{6}H\textsubscript{6} and CO\textsubscript{2} impurities are controlled to below 0.1, 4 and 50 ppm, respectively. Significant effort has been invested into measuring and modelling the thermodynamic and kinetic aspects of the freeze-out phenomena. However, this problem is likely to be more severe for hydrogen liquefaction given both the additional impurity compounds that may freeze out (N\textsubscript{2}, O\textsubscript{2}, CH\textsubscript{4}, Ar), the even lower (ppt) solubilities in H\textsubscript{2} at cryogenic temperatures, and the catalyst-packed plate and fin heat exchangers used. While existing plants employ adsorbers to remove these impurities, this may not be sufficient for larger plants (> 50 TPD), particularly if allowable tolerances on impurity concentrations do not have a robust basis. Accordingly, the void of solubility and freeze-out kinetic data for relevant impurities in cryogenic H\textsubscript{2} should be addressed through laboratory measurements, leading to the development of predictive engineering models. The efficacy of adsorbent materials and processes to remove these impurities to the requisite levels should also be investigated further to identify possible opportunities for optimising cost and performance. Finally, the adaptation of similar sensor technologies developed to provide real-time information on the freeze-out risk of impurities in LNG production\textsuperscript{71} should be considered.

6 Conclusions and outlook

Global demand for hydrogen is projected to rise from 75 million tonnes in 2019 to 621 million tonnes in 2050. Hydrogen liquefaction is likely to be a key technology enabling the growth of hydrogen transport and storage needed to meet projected global demand. Whilst it is one several technologies available, including ammonia and liquid organic carriers, LH\textsubscript{2} offers several advantages including being an immediately pure product at the point of use. However, multiple challenges exist to the growth of liquid hydrogen, which can be placed within the broad categories of economics, cryogenic losses, safety and scale. By reviewing the current status of hydrogen liquefaction, from the fundamental physics to current engineering practice, this paper has sought to highlight the key barriers and identify potential solutions needed if LH\textsubscript{2} is to have a substantial role in the world’s future energy value chain.

Two key targets for future liquid hydrogen supply chains are (i) reducing the specific liquefaction cost to around (1–2) US$ per kg\textsubscript{H\textsubscript{2}}\textsuperscript{−1}, and (ii) lowering the specific energy consumption of the liquefaction process to between (6 and 8) kWh kg\textsubscript{H\textsubscript{2}}\textsuperscript{−1}. These targets should be achievable if liquefaction train capacities can be increased to around 100 TPD or larger. Currently, global liquefaction capacity is around 350 TPD with a further 96 TPD planned; the capacity of the largest single train is 32 TPD. Current commercial processes have SECs from (11.9 to 15) kWh kg\textsubscript{H\textsubscript{2}}\textsuperscript{−1} (or 35 to 45% of the stored energy content), and SLCs around (2.5–3) US$ per kg\textsubscript{H\textsubscript{2}}\textsuperscript{−1}, which is larger than the current cost of producing blue hydrogen. Achieving these targets will therefore require significant advances in the design and operation of hydrogen liquefaction facilities.
Hydrogen liquefaction plants that achieve these targets will likely use mixed-refrigerants in both the pre-cooling and cryogenic stages of a Brayton cycle, integrated and modular cold box configurations, high-efficiency turbo compressors on the refrigerant-side, and oil-free expanders for the H2 side. Ortho–para conversion will be more efficient using catalysts with better characterised kinetics integrated into heat exchanger designs that reduce the associated pressure drop. Potentially, LH2 storage and transport systems might utilise densification and slush hydrogen technologies to minimise boil-off losses and increase storage capacity. Improved models for quantitative predictions of thermal stratification, interfacial heat transfer, tank geometry, pressure and the resulting LH2 boil off rate in large storage tanks will be essential. Finally, if large-scale liquid hydrogen supply chains are to become a reality, addressing the challenge of safety will be vital through a combination of standards development and improved technologies for automatically detecting and eliminating hydrogen leaks and fires.

To help reach these goals, this paper first summarised the current state-of-the-art for knowledge and technology across the LH2 supply chain, and then presented a list of research, development and demonstration priorities in Table 10. While not exhaustive, over forty opportunities and topics are listed covering liquefaction (e.g. process & equipment design, ortho–para conversion), storage & transport (e.g. tank design, shipping & custody transfer, safety), and fundamentals (e.g. fluids, catalysts, sensors). Addressing this range of research, and development opportunities will require a concerted and collaborative effort by both industry and academia, with significant investments of expertise and new infrastructure for laboratory measurements, pilot-scale demonstrations and ultimately industrial-scale deployment.

Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al2O3</td>
<td>Aluminium oxide</td>
</tr>
<tr>
<td>APEC</td>
<td>Asia Pacific Economic Cooperation</td>
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<tr>
<td>APERC</td>
<td>Asia Pacific Energy Research Centre</td>
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<tr>
<td>Ar</td>
<td>Argon</td>
</tr>
<tr>
<td>AUD</td>
<td>Australian dollar</td>
</tr>
<tr>
<td>BOG</td>
<td>Boil-off gas</td>
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<tr>
<td>CAPEX</td>
<td>Capital expenditures</td>
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<tr>
<td>CCS</td>
<td>Carbon capture and storage</td>
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<tr>
<td>CG</td>
<td>Coal gasification</td>
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<tr>
<td>CGH2</td>
<td>Compressed hydrogen gas</td>
</tr>
<tr>
<td>CH4</td>
<td>Methane</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
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<tr>
<td>Co(OH)3</td>
<td>Cobalt hydroxide</td>
</tr>
<tr>
<td>CO2</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>COX</td>
<td>Oxide of carbon</td>
</tr>
<tr>
<td>Cr2O3</td>
<td>Chromium oxide</td>
</tr>
<tr>
<td>CrO</td>
<td>Chromium oxide</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of thermal expansion</td>
</tr>
<tr>
<td>DOE</td>
<td>US Department of Energy</td>
</tr>
<tr>
<td>EOS</td>
<td>Equations of state</td>
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<td>EU</td>
<td>European union</td>
</tr>
<tr>
<td>EUR</td>
<td>Euros</td>
</tr>
<tr>
<td>FCH JU</td>
<td>Fuel cells and hydrogen joint undertaking</td>
</tr>
<tr>
<td>FCV</td>
<td>Fuel cell vehicle</td>
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<td>Fe2O3</td>
<td>Iron(III) oxide</td>
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<td>GJ</td>
<td>Gigajoule</td>
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<td>Nitrogen gas</td>
</tr>
<tr>
<td>GPD</td>
<td>British pound</td>
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<td>H2</td>
<td>Hydrogen</td>
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<tr>
<td>H2O</td>
<td>Water</td>
</tr>
<tr>
<td>He</td>
<td>Helium</td>
</tr>
<tr>
<td>IDEALHY</td>
<td>Integrated design for efficient advanced liquefaction of hydrogen</td>
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<tr>
<td>IEC</td>
<td>International electrotechnical commission</td>
</tr>
<tr>
<td>IRAS</td>
<td>Integrated refrigeration and storage</td>
</tr>
<tr>
<td>ISO</td>
<td>International organization for standardization</td>
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<tr>
<td>JPY</td>
<td>Japanese Yen</td>
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<tr>
<td>J-T</td>
<td>Joule–Thomson</td>
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<tr>
<td>K</td>
<td>Kelvin</td>
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<tr>
<td>kg</td>
<td>Kilogram</td>
</tr>
<tr>
<td>KHI</td>
<td>Kawasaki heavy industries</td>
</tr>
<tr>
<td>kJ</td>
<td>Kilojoule</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt-hour</td>
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<tr>
<td>LCOH</td>
<td>Levelised cost of hydrogen</td>
</tr>
<tr>
<td>LH2</td>
<td>Liquid hydrogen</td>
</tr>
<tr>
<td>LHV</td>
<td>Lower heating value</td>
</tr>
<tr>
<td>LN2</td>
<td>Liquid nitrogen</td>
</tr>
<tr>
<td>LNG</td>
<td>Liquefied natural gas</td>
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<tr>
<td>LOHC</td>
<td>Liquid organic hydrogen carriers</td>
</tr>
<tr>
<td>m3</td>
<td>Cubic meter</td>
</tr>
<tr>
<td>MeOH</td>
<td>Methanol</td>
</tr>
<tr>
<td>meV</td>
<td>Millielectronvolt</td>
</tr>
<tr>
<td>MJ</td>
<td>Megajoule</td>
</tr>
<tr>
<td>mm</td>
<td>Millimetres</td>
</tr>
<tr>
<td>MPa</td>
<td>Megapascal</td>
</tr>
<tr>
<td>MRs</td>
<td>Mixed refrigerants</td>
</tr>
<tr>
<td>Mtpa</td>
<td>Million tonnes per annum</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt</td>
</tr>
<tr>
<td>N2</td>
<td>Nitrogen</td>
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<td>N2O</td>
<td>Nitrous oxide</td>
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<tr>
<td>NASA</td>
<td>US National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>Ne</td>
<td>Neon</td>
</tr>
<tr>
<td>NFPA</td>
<td>National fire protection association</td>
</tr>
<tr>
<td>NH3</td>
<td>Ammonia</td>
</tr>
<tr>
<td>NiO</td>
<td>Nickel(II) oxide</td>
</tr>
<tr>
<td>Nm3</td>
<td>Normal cubic meter</td>
</tr>
<tr>
<td>NOx</td>
<td>Nitrogen oxides</td>
</tr>
<tr>
<td>O2</td>
<td>Oxygen</td>
</tr>
<tr>
<td>OP</td>
<td>Operating expenses</td>
</tr>
<tr>
<td>PFHE</td>
<td>Plate-finned heat exchangers</td>
</tr>
<tr>
<td>Pnet</td>
<td>Net power consumption</td>
</tr>
</tbody>
</table>
ppb  Parts per billion
PV  Photovoltaic
rpm  Revolutions per minute
SEC  Specific energy consumption
SLC  Specific liquefaction cost
SMR  Steam methane reforming
THz  Terahertz
TPD  Tons per day
USA  United States of America
USD  United States dollar
VLE  Vapour–liquid equilibrium
wt%  Percentage by weight

Author contributions


Conflicts of interest

There are no conflicts to declare.

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