Narrative Review Article

Electrochemical Hydrogen Compression: Thermodynamic Advantages and Practical Constraints Relative to Mechanical Systems

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ABSTRACT

The growing limitations of fossil fuel dependence have accelerated interest in hydrogen as a clean energy carrier. However, hydrogen's low volumetric energy density necessitates compression, introducing thermodynamic inefficiencies and material challenges that impact system performance. Mechanical hydrogen compressors currently dominate due to technological maturity and scalability, but operate under non-ideal conditions characterised by near-adiabatic behaviour, frictional losses, and material degradation. Electrochemical hydrogen compression presents an alternative approach, offering near-isothermal operation, reduced mechanical losses, and integrated purification. Despite these theoretical advantages, its performance is constrained at higher pressures by hydrogen crossover, membrane limitations, and accumulating electrochemical irreversibility. This review evaluates mechanical and electrochemical hydrogen compression within a unified thermodynamic framework, linking performance limitations to their underlying physical mechanisms. The analysis shows that electrochemical compression offers higher efficiency at low-to-moderate pressures, while mechanical compression remains more practical for high-pressure, large-scale applications. Furthermore, the findings highlight key trade-offs and identify critical research directions required to improve electrochemical compressor performance and enable broader adoption within future hydrogen energy systems.

Keywords: hydrogen compression; electrochemical compression; mechanical compressor; hydrogen crossover; hydrogen economy; near-isothermal compression; adiabatic compression; thermodynamic analysis

INTRODUCTION

Over the past century, most of the world's energy consumption has come from fossil fuels such as coal, oil, and natural gas. This reliance on fossil fuels has led to increased greenhouse gas emissions and therefore contributed greatly to global warming and climate change. These gas emissions coupled with co-emitted air pollutants such as sulfur dioxide, nitrogen oxides and particulate matter, contribute to smog, acid rain, and increased cardiopulmonary morbidity (1). Furthermore, fossil fuels are finite, have volatile international markets, and their extraction is destructive to the environment (2, 3).

To combat this, hydrogen-based systems have received increasing investment and policy support across the globe. Hydrogen is a clean energy carrier: when

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produced via renewable electrolysis (green hydrogen) and used in fuel cells, it emits only water vapor, eliminating CO_2 and other pollutants. Additionally, hydrogen does not involve destructive extraction and can be produced renewably from water using electricity.

However, hydrogen has a very low density, so even though it has a substantially higher energy content per unit mass than fossil fuels, fossil fuels possess a much higher energy content per unit volume under ambient conditions. Therefore, to make hydrogen a viable replacement, it is generally stored and transported under high pressures (350–700 bar for vehicles, up to ~1000 bar in niche or experimental storage systems). Other ways to increase hydrogen's volumetric energy density include cryogenic cooling and chemical hydrogen carriers, but alternative processes as such involve higher energy penalties due to slow kinetics, boil-off and other inefficiencies (4). These alternatives may be advantageous in specific logistical contexts such as long-distance transport, seasonal storage, infrastructure compatibility, and specific high energy or safety constrained applications. This review paper does not explore these processes, rather strictly focusing on alternatives within hydrogen compressors.

The two prevailing types of hydrogen compressors are mechanical hydrogen compressors (MHCs) and electrochemical hydrogen compressors (EHCs). In 2024, the market for hydrogen compressors was dominated by mechanical compressors due to technological maturity and scalability (3). However, electrochemical compressors exhibit potential due to near isothermal single stage compression, reduced frictional losses, better purification and other promising characteristics that help reduce energy consumption. Furthermore, hydrogen's unique properties lead to thermodynamic and material challenges including deviation from ideal gas behaviour, substantial and rapid heat generation, hydrogen embrittlement, and other inefficiencies. These challenges emphasise the importance of optimised compression technology. This review explores how electrochemical compression helps mitigate the effects of hydrogen complications compared to mechanical compression, while also providing a comparative analysis on electrochemical compressors against mechanical compressors at the current moment, which includes limitations within electrochemical compression and what research may help electrochemical compression serve as a more viable option in the future.

COMPLICATIONS WITH HYDROGEN COMPRESSION

Hydrogen compression is fundamentally constrained by intrinsic properties of hydrogen that persist regardless of the compression method used. Key challenges include deviation from ideal gas behaviour, heat generation during compression, and hydrogen embrittlement. These factors collectively increase the work required for compression and reduce overall system efficiency.

Deviation from an ideal gas

Hydrogen compression is often initially described using the ideal gas law, which assumes an inverse relationship between pressure and volume at constant temperature. Under ambient conditions (~1 bar, 298 K), 1 m^3 of hydrogen has a mass of approximately 90 g; at 700 bar, this increases to around 42 kg, reflecting the substantial increase in volumetric energy density achieved through compression.

However, at elevated pressures, hydrogen increasingly deviates from ideal behaviour due to intermolecular interactions and finite molecular volume. The real gas equation, $PV = ZnRT$, introduces the compressibility factor Z, which accounts for these effects. Experimental data indicate that at ~300 bar, $Z \approx 2$, implying that ideal gas models significantly underestimate the work required for compression (5-6).

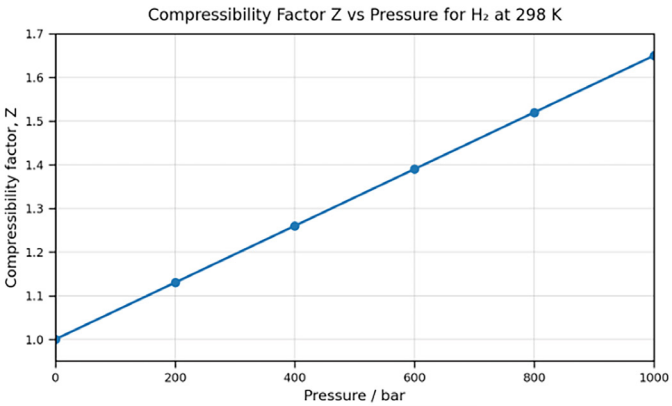

Figure 1. *Compressibility factor Z of hydrogen versus pressure at 298 K. Pressure is shown in bar, and Z is dimensionless. Data were calculated from NIST thermodynamic properties using Z = PV/nRT.*

As demonstrated in Figure 1, Z scales with pressure due to repulsive molecular interactions and volume. Values of Z significantly increase operational energy

demand as pressure rises above ~200 bar, therefore explaining the measurable significance of real-gas effects in hydrogen compression to high pressures. Quantitative studies support this observation. For example, Kee *et al.* (2019) report that isothermal compression from ~1–1000 bar requires approximately 0.2 kWh/kg-H_2 more energy than predicted by ideal gas models (7). Similarly, polytropic compression analyses incorporating real-gas behaviour suggest that the minimum work required for compression from ~1–700 bar may be up to ~25% higher than the ideal isothermal value (8).

Collectively, these findings indicate that real-gas effects impose a non-negligible thermodynamic penalty, particularly at high pressures. This is further reflected in density estimates: while ideal scaling predicts ~63 kg/m³ at 700 bar, actual values are closer to ~42 kg/m³, highlighting the reduced compressibility of hydrogen under real conditions.

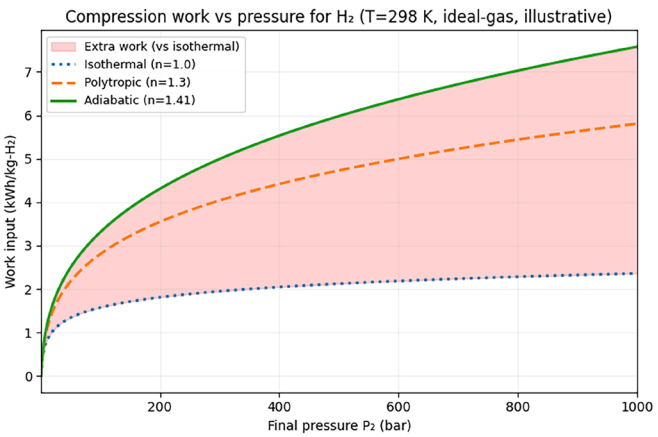

Figure 2. *Theoretical compression work required to compress hydrogen from 1 bar to a final pressure P_2 at 298 K under isothermal (n = 1), polytropic (n = 1.3), and adiabatic (n = 1.41) conditions. The x-axis shows final pressure P_2 (bar), and the y-axis shows specific compression work (kWh kg^{-1} H_2). The shaded region represents the additional work required relative to ideal isothermal compression.*

Heat Loss and Efficiency Penalties in Adiabatic Compression

To increase the volumetric energy density of hydrogen, input work must be supplied to raise its pressure, thereby increasing the number of moles stored per unit volume, which directly relates to volumetric energy density. However, if the rate of heat removal is insufficient, part of this work input increases the internal energy of the gas, raising its temperature during compression, as stated in the equation below:

$$dU = \delta W - \delta Q \qquad \text{(Eq. 1)}$$

δW is the mechanical or electrochemical work input and δQ is heat removed from the system.

In the case of insufficient heat removal, compression moves towards quasi-adiabatic conditions: the rate of instantaneous heat removal (δQ) cannot keep up with that of compression work (δW), which leads to a net increase in internal energy and therefore temperature during compression (Adiabatic conditions assume zero heat removal).

Since storage occurs at ambient temperatures, the temperature rise during compression must be dissipated to the surroundings before use, generating entropy and destroying exergy. Consequently, the actual energy input required to achieve a given volumetric energy density is higher under adiabatic conditions (7). The thermodynamic penalty associated with non-isothermal compression can be quantified using ideal-gas compression work relations for different paths, as illustrated below.

The divergence in Figure 2 between isothermal and adiabatic work increases with final pressure, indicating that thermal management becomes progressively more critical at higher compression ratios. It should be noted that these curves represent ideal-gas, path dependent work and do not account for additional real world irreversibilities such as internal temperature gradients, non-uniform heat transfer, mechanical friction, pressure losses, or material degradation effects (e.g., hydrogen embrittlement). In practical systems, these factors further increase entropy generation and therefore raise the actual work demand beyond the estimates shown, amplifying the energetic penalty of non-isothermal compression.

Franco and Giovannini (2024) report that, for commercial compressors with a total ratio of 350, the specific work ranges from about 10 MJ/kg for larger units to over 26 MJ/kg for smaller ones, highlighting how real systems can substantially exceed theoretical minimums. This value reflects entropy generation as well as real gas behaviour described in Section 2.1, emphasising the importance of thermal management and optimised compression (8).

Hydrogen has unique physical properties which make it especially prone to rapid and substantial heat generation. Firstly, hydrogen has a relatively high heat capacity ratio ($\gamma \approx 1.4$ at ambient conditions) and a low

number of internal energy modes. During adiabatic compression, temperature rise scales with pressure ratio according to the equation below:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{((\gamma-1)/\gamma)} \quad \text{(Eq. 2)}$$

Therefore, a higher γ results in a larger temperature increase for a given pressure ratio, increasing the need for effective thermal management (8).

In addition, hydrogen has an exceptionally low density, resulting in a low volumetric heat capacity (ρCp) For a given energy input per unit volume q, the resulting temperature rise is:

$$\Delta T = \frac{q}{(pCp)} \quad \text{(Eq. 3)}$$

This implies that hydrogen heats up rapidly during compression and requires proportionally greater heat removal to return to ambient conditions (7, 8).

Experimental and simulation studies further illustrate these effects. Ye *et al*. (2023) conducted computational fluid dynamics (CFD) simulations of hydraulic-driven piston hydrogen compressors and observed that heat transfer within the cylinder causes exhaust temperatures to deviate by up to 6.29 K from ideal adiabatic predictions during the compression stroke (10). This deviation highlights the practical challenges in achieving near-isothermal compression and underscores the role of thermal management in reducing inefficiencies.

Hydrogen embrittlement

Hydrogen embrittlement is defined as the deterioration of ductility and fracture toughness of a metal due to the absorption of hydrogen atoms. Chemisorption results in hydrogen molecules dissociating into atoms near the metal surface (11). These atoms then diffuse into the metal lattice into microstructural defects such as grain boundaries, dislocations, and voids. This diffusion scales with pressure; this is because as pressure rises, more atoms are close to the metal surface, and so more diffuse into it. Diffusion leads to mechanisms that collectively reduce the stress required for crack initiation and propagation: hydrogen-enhanced decohesion (HEDE) weakens atomic bonds at crack tips, hydrogen-enhanced localised plasticity (HELP) concentrates deformation locally, and hydrogen-induced vacancy formation nucleates internal cracks (11). In susceptible high strength steels common to hydrogen compressors, this results in brittle fracture and fatigue crack growth rates orders of magnitude faster than in inert environments (12).

HYDROGEN COMPRESSORS

This section explores the function of mechanical and electrochemical compressors and how they relate to the hydrogen complications described in section 2.

Mechanical Hydrogen Compressors

Mechanical compressors involve the use of a moving boundary, which usually takes the form of reciprocating pistons, diaphragm compressors, or liquid pistons. The moving boundary physically does positive work on the gas, which reduces its volume.

The mechanical work associated with this volume reduction is described by the moving-boundary work relation:

$$\delta W = -PdV \quad \text{(Eq. 4)}$$

In the case of mechanical compression, volume must be reduced, as a result dV<0. This implies that positive work is required to compress hydrogen, which is supplied by the moving boundary. The change in internal energy is related to the work done by the equation below.

$$dU = \delta W - \delta Q \quad \text{(Eq. 5)}$$

Unless heat is removed at the same rate as work input, a significant fraction of the applied work is stored as internal energy, resulting in a temperature rise.

During mechanical compression, the rate of work input is significantly greater than the rate of heat removal. The moving boundary transfers energy on a millisecond timescale, whereas heat removal occurs over seconds to minutes. As a result, heat transfer during a single compression stroke is limited. For example, Kermani and Rokni (2015) simulated a liquid-piston hydrogen compressor and found that hydrogen temperature was reduced by only 0.2–0.4% from the adiabatic prediction, indicating that heat transfer during the stroke has a negligible influence on the thermodynamic path (13).

Heat removal is primarily governed by conduction at the walls and convection at external surfaces, both of which are diffusive and inherently slow processes. Consequently, for a single compression interval, heat removal can be approximated as negligible ($\delta Q \approx 0$). Unless active cooling strategies are implemented, this behaviour extends across the compression process, resulting in near-adiabatic conditions for single stage mechanical compression without intercooling.

$$dU = \delta W - \delta Q \quad \text{(Eq. 6)}$$

Under these conditions, where $\delta Q \approx 0$, most of the input work contributes to an increase in internal energy, which manifests as a temperature rise in the hydrogen. As discussed previously, this temperature rise is thermodynamically inefficient, as the gas must subsequently be cooled to ambient storage conditions, resulting in exergy destruction. Therefore, achieving a given final pressure requires greater input work than ideal isothermal compression (8, 10).

Thermodynamic estimates further illustrate this penalty. For hydrogen (γ = 1.41), adiabatic compression from 10 to 250 bar yields a temperature ratio $T_f / T_i \approx 2.55$, while a polytropic process (n = 1.3) requires approximately 48% more work than ideal isothermal compression. These results highlight the significant energetic cost associated with non-isothermal compression. Although multistage compression with intercooling reduces this penalty, it cannot eliminate it, as heat removal rates remain inherently limited relative to mechanical work input.

Additional inefficiencies arise from non-uniform conditions within the compressor. The piston imparts energy locally, causing gas near the piston to reach higher temperatures than gas farther away, resulting in internal temperature and pressure gradients. This deviation from quasi-equilibrium behaviour introduces further irreversibility. Prasad (1992) measured temperature differences of approximately 28°C across reciprocating compressor cylinders during operation, with peak temperatures near the piston (14). The relaxation of these gradients through heat conduction and viscous mixing is irreversible, generating entropy and increasing the required compression work.

Localised temperature increases near pistons, seals, and valves also accelerate hydrogen embrittlement. Elevated temperatures enhance hydrogen diffusion into metallic components, while subsequent cooling can trap hydrogen atoms within the lattice. When combined with cyclic mechanical stresses, this process exacerbates material degradation in mechanical compression systems (15).

Mechanical compressors also experience frictional and throttling losses associated with pistons, valves, bearings, leakage paths, and pressure drops. These losses convert useful mechanical work into heat without contributing to pressure increase, representing additional sources of entropy generation (9, 16). Studies indicate that piston ring friction alone can account for a significant fraction of mechanical losses, with valve throttling and bearing friction contributing further inefficiencies.

In addition, structural components in mechanical compressors are exposed to repeated pressure cycles, leading to fatigue loading. Experimental measurements by Slifka *et al.* (2014) showed that fatigue crack growth rates in pipeline steels exposed to pressurised hydrogen are significantly higher than in air, demonstrating the detrimental impact of cyclic hydrogen environments on material durability (17).

Collectively, these findings indicate that mechanical compression is constrained by a combination of thermodynamic, thermal, and material limitations, all of which contribute to increased energy demand and reduced system longevity.

Electrochemical Hydrogen Compressors

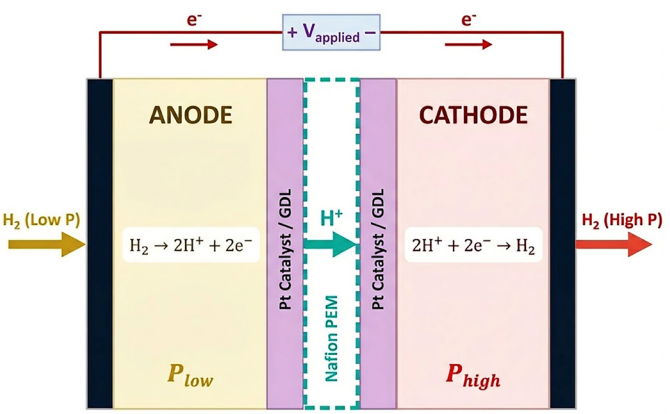

Figure 3. *Schematic of a PEM-based electrochemical hydrogen compressor. Low pressure hydrogen is oxidised at the anode ($H_2 \rightarrow 2H^+ + 2e^-$), protons are transported through the Nafion membrane under an applied voltage, and high-pressure hydrogen is recovered at the cathode ($2H^+ + 2e^- \rightarrow H_2$).*

As illustrated in Figure 3, electrochemical hydrogen compressors follow a structure similar to proton-exchange membrane (PEM) fuel cells. The system consists of two electrodes separated by a proton-exchange polymer membrane that conducts hydrogen ions while blocking electrons and gas molecules. Low pressure hydrogen is oxidised at the anode into protons and electrons. The protons are transported across the membrane by an electrochemical potential gradient, while the electrons travel through an external circuit driven by an applied voltage. At the cathode, protons and electrons recombine to form hydrogen gas at higher

pressure. As a result, compression work is supplied electrically rather than mechanically.

While PEM-based electrochemical compression represents the most experimentally demonstrated and developed architecture, several alternative systems have been explored. These include high-temperature proton-conducting ceramic membranes, which can reduce ohmic losses at elevated temperatures; alkaline anion-exchange membrane compressors, which aim to reduce reliance on platinum-group catalysts; and metal hydride electrochemical systems, which compress hydrogen through reversible hydriding reactions driven electrochemically (7, 18, 19).

In PEM-based electrochemical hydrogen compressors, electrical work directly increases hydrogen pressure. According to the relation $\Delta G = -nF\Delta E$, an applied voltage raises the Gibbs free energy of the hydrogen system. Since chemical potential is defined as the molar Gibbs free energy at constant temperature and pressure, and for an ideal gas $\mu = \mu^\circ + RT\ln(P/P^\circ)$, an increase in electrical input corresponds to an increase in chemical potential and therefore pressure (20).

(R = gas constant, T = temperature, P = pressure)

Hydrogen's deviation from ideal gas behaviour ($Z > 1$ at high pressures) is an intrinsic property of the gas and therefore independent of the compression method used. Consequently, real-gas effects impose a minimum thermodynamic work requirement that cannot be eliminated by any compression technology. In contrast, electrochemical hydrogen compression does not involve a moving boundary and therefore avoids the timescale mismatch observed in mechanical systems. Electrical work is supplied continuously, while heat is removed through coolant plates at a comparable rate, resulting in closely aligned timescales.

As a result, electrochemical compressors can approach near-isothermal behaviour under controlled conditions. This leads to minimal temperature rise; for example, electrochemical compression at operating current densities of approximately 500–2000 mA cm^{-2}, with coolant flow rates of 0.1–0.5 L min^{-1} per cell, has been reported to produce temperature increases of less than 2 K at discharge pressures of around 10 bar (21). In addition, electrochemical compression distributes energy input across the membrane–electrode interface rather than concentrating it at a moving boundary, allowing operation closer to reversible compression and reducing thermodynamic irreversibility (7). The absence of moving mechanical components eliminates frictional losses and enables quieter operation. Demonstration studies report hydrogen recovery efficiencies exceeding 95%, with compression achieved through electrochemical proton transport rather than mechanical work (21). Consequently, electrochemical systems avoid the significant heat dissipation losses associated with mechanical compressors and can, in principle, approach the isothermal efficiency limit of approximately 2.24 kWh/kg.

Material considerations further support this distinction. Compression occurs within polymeric membranes and porous electrodes rather than high-strength structural steels, reducing susceptibility to hydrogen embrittlement. In addition, high pressure regions are typically confined by graphite or thin metallic bipolar plates that are not subjected to significant cyclic mechanical stresses, thereby reducing embrittlement related degradation (22).

A COMPARATIVE ANALYSIS BETWEEN MECHANICAL HYDROGEN COMPRESSORS AND ELECTROCHEMICAL HYDROGEN COMPRESSORS TODAY

Table 1 summarises these dimensions at a high level. The following analysis examines each in detail, identifying the thermodynamic origins of the trade-offs observed. From the review, it is evident that electrochemical hydrogen compressors (EHCs) offer more efficient energy pathways than mechanical hydrogen compressors (MHCs) in theory. This advantage arises primarily from the absence of moving boundaries, negligible frictional and throttling losses, the ability to operate under near-isothermal conditions, and reduced susceptibility to hydrogen embrittlement. In contrast, mechanical compressors involve rapid moving-boundary work that significantly exceeds the rate of heat removal. This imbalance leads to near-adiabatic conditions which, when combined with internal thermal gradients and frictional losses, result in entropy generation. Consequently, the work required exceeds the ideal isothermal minimum, while cyclic thermal and mechanical stresses further accelerate material degradation.

These inefficiencies have driven the development of improved mechanical compression technologies, including multistage systems, liquid piston compressors, and other thermodynamically optimised designs. However, such approaches primarily mitigate rather than eliminate the fundamental limitations associated with moving-boundary compression. As a result,

Table 1. *Key comparative dimensions of mechanical hydrogen compressors (MHCs) and electrochemical hydrogen compressors (EHCs).*

Dimension	MHC	EHC
Thermal behaviour	Near-adiabatic; high entropy generation	Near-isothermal under controlled conditions; minimal temperature rise
Friction & throttling losses	Significant losses; pistons, valves, bearings contribute	Negligible losses; no moving parts
Embrittlement risk	High risk; cyclic mechanical stress on structural steel components	Low risk; compression occurs in polymeric membrane and electrodes
High-pressure performance	4–6 kWh/kg at 700 bar; technologically mature	6–12 kWh/kg at 700 bar under current conditions; degrades with pressure
Purity	Lubricant contamination risk; no integrated purification	High purity output but requires high-purity inlet feed
Capital cost	~1,000–2,500 USD per kg·day (mature, scalable)	~150–1,700 USD per kg·day capacity (strongly scale dependent; significantly increases once durability drops, which it does comparatively quickly)
Technology maturity	Commercially mature; widely deployed for 350–700 bar refuelling and pipeline service.	Emerging; limited long-term data

alternative technologies such as EHCs have been increasingly explored due to their higher theoretical efficiency ceilings. From a thermodynamic perspective, electrochemical pathways therefore appear favourable; however, this advantage is not consistently maintained at higher pressures.

The reduction in electrochemical performance at elevated pressures is largely attributed to hydrogen back-diffusion. Hydrogen crossover from the high-pressure cathode to the low-pressure anode increases with cathode pressure and can significantly reduce current efficiency at high operating conditions (18, 23). In addition, higher pressure differentials impose mechanical stress on proton-exchange membranes, increasing the risk of structural degradation or rupture (18, 24). To address these challenges, thicker membranes are often employed. While this reduces crossover and improves mechanical stability, it also increases ionic transport resistance, leading to higher ohmic losses. As a result, operating voltages increase for a given current density, directly increasing specific energy consumption (25).

This trade-off highlights a fundamental design constraint: thinner membranes reduce electrical resistance and improve efficiency but compromise mechanical strength and increase hydrogen crossover, whereas thicker membranes enhance durability and reduce crossover at the expense of higher energy consumption. Consequently, membrane optimisation remains a critical limitation in achieving high-pressure electrochemical compression.

To reach higher pressures, electrochemical compressors are typically arranged in series, with each cell contributing a fraction of the total pressure increase. Current systems can achieve pressures up to approximately 700 bar through multi-stage electrochemical stacking, with individual stages contributing on the order of 10–100 bar. However, although this approach maintains near-isothermal conditions within each stage, it does not preserve the same level of energy efficiency observed at lower pressures.

This is because electrochemical irreversibilities accumulate across the stack. While serial stacking resolves per-cell pressure limitations, it does not eliminate activation, ohmic, and concentration losses, all of which increase with operating pressure and current density. Unlike multistage mechanical compression, electrochemical systems do not benefit from intercooling or thermodynamic "reset" stages. As a result, losses compound across the system, leading to increased overall energy consumption.

Empirical data reflect this trend. Electrochemical compressors have historically required approximately 6–12 kWh/kg for compression from low pressure to ~3000 psi, with reported cases of around 6.2 kWh/kg for pressures up to ~12,500 psi (16, 21). More recent

systems achieve improved performance, with values of approximately 2–4 kWh/kg up to 350 bar under optimised conditions. However, energy consumption increases significantly at higher pressures and throughput levels, limiting large-scale deployment. In contrast, well-designed mechanical compressors with intercooling typically operate at approximately 4–6 kWh/kg for compression to 700 bar (26-27), demonstrating more stable performance at high pressures. It should be noted, however, that these values depend strongly on system scale, throughput, cooling strategies, and operational conditions.

Collectively, these findings indicate that electrochemical compressors are more energy efficient at low-to-moderate pressures and lower throughput conditions, but their performance deteriorates at higher pressures due to increasing electrochemical irreversibilities. Further advances in membrane materials and stack design are therefore required to extend electrochemical efficiency to higher pressure regimes.

In terms of hydrogen purity, electrochemical compressors offer a distinct advantage. The proton-exchange membrane acts as a selective barrier, allowing only hydrogen ions to pass while rejecting contaminants. This enables simultaneous compression and purification, and the absence of moving parts eliminates the risk of lubricant contamination, making EHCs particularly suitable for high-purity applications such as fuel cell systems (23).

However, this advantage is conditional. Studies by Nordio *et al*. (23) show that compressor performance degrades with reduced inlet hydrogen concentration, indicating sensitivity to impurities and mass transport limitations. Additionally, platinum-based catalysts used in many EHC systems are susceptible to poisoning by contaminants such as carbon monoxide and sulphur compounds (28). As a result, deviations from high-purity feed conditions can significantly reduce performance. While partial recovery of performance may be achieved through voltage cycling or oxidative treatments, these processes introduce operational complexity and may accelerate degradation of the membrane–electrode assembly (29). Consequently, the requirement for high-purity inlet hydrogen represents a practical limitation, reducing the overall advantage of integrated purification.

From a cost perspective, mechanical compressors currently retain an advantage in high-pressure applications. Mature systems typically have capital costs in the range of 1000–2500 USD per kg·day of installed capacity, with specific energy consumption of approximately 4–6 kWh/kg, resulting in compression costs of around 0.3–0.8 USD per kg H_2 under industrial conditions (16, 26, 27, 30). Electrochemical compressors may offer lower capital costs at small scales (approximately 150–1700 USD per kg·day), but their economic viability is limited by lower throughput capacity and reduced durability, with reported operational lifetimes often below 10,000–15,000 hours (24). These factors increase replacement frequency and operational costs.

Overall, the evidence suggests that electrochemical hydrogen compressors are currently better suited to low-pressure (<200 bar), low-throughput, and high-purity applications, particularly in distributed or modular systems. In contrast, mechanical compressors remain more economically and operationally viable for large-scale, high-pressure applications such as refuelling infrastructure and pipeline compression.

FINAL CONCLUSIONS AND SCOPE FOR FUTURE RESEARCH

In summary, electrochemical hydrogen compression demonstrates higher theoretical thermodynamic efficiency and integrated purification compared to mechanical compression. However, its performance declines at higher pressures and throughput due to hydrogen crossover, membrane mechanical constraints, and accumulating electrochemical irreversibility. Mitigation strategies, such as thicker membranes, reduce crossover but increase ohmic losses, while stack degradation and limited lifetimes raise lifecycle costs. As a result, EHCs are currently more suitable for low-pressure, low-flow, high-purity applications, whereas multistage mechanical compressors remain more practical for high-pressure, large-scale operation. Nevertheless, the theoretical advantages of EHCs provide strong motivation for further development, as overcoming these limitations could significantly improve efficiency and reduce energy consumption. Addressing the research gaps identified in this review is therefore essential.

A comprehensive thermodynamic comparison between real-world mechanical and electrochemical compressors represents a critical next step. Such analysis should be conducted within a unified, empirically grounded framework that incorporates real-gas behaviour, degradation, impurities, balance-of-plant penalties, and other non-ideal losses. Applying consistent thermodynamic assumptions and boundary conditions

across both technologies would enable more rigorous and comparable evaluation across a continuous pressure range. Existing reviews often focus on performance metrics without maintaining such consistency; therefore, a unified comparative framework would significantly improve analytical clarity and support further innovation. A corresponding techno-economic comparison would also be valuable.

Improving electrochemical compressor performance at higher pressures requires advancements across multiple technological levels. At the material level, membrane development is critical. Future research should focus on increasing mechanical strength without incurring additional ohmic losses, thereby addressing the trade-off between durability and energy efficiency. Current studies explore composite and mechanically supported membrane–electrode assemblies capable of maintaining conductivities above 0.1 S/cm at pressures exceeding 700 bar, as well as ionomers with improved chemical stability under cyclic operation (24, 28).

At the catalyst and electrode level, platinum-based systems remain costly, impurity-sensitive, and subject to mass-transport limitations at high current densities. Consequently, optimisation strategies are required to improve performance and reduce cost. Current research includes ultra-low platinum loadings through sputtering, bimetal alloy catalysts to enhance activity and durability, and non-noble alternatives to improve resistance to contamination under realistic operating conditions (22, 28, 31).

At the stack level, serial stacking introduces cumulative irreversibility as well as pressure and thermal gradients. Future work should therefore focus on maintaining near-isothermal conditions and reducing efficiency losses that scale with stack size and pressure. Approaches such as pressure-graded configurations, optimised flow field designs, and improved thermal management strategies are currently being investigated. Experimental studies suggest that circular cell geometries may offer performance benefits, although their scalability remains uncertain (24).

In addition, long-term degradation behaviour of electrochemical compressors remains insufficiently characterised. Most experimental studies are limited to operational durations of 1000–3000 hours, making lifetime projections uncertain. Extended durability testing is required to validate targets exceeding 30,000 hours and to better understand failure mechanisms (24, 28).

Further empirical evaluation of balance-of-plant systems and high-pressure electrochemical compressors is also necessary. Current performance models remain limited without sufficient experimental validation at elevated pressures, highlighting the need for continued large-scale testing (22).

Ultimately, advancing EHC technology could unlock a new paradigm in hydrogen compression that mitigates the effects of hydrogen's molecular complications while meeting energy, purity and cost demands of the compressor market. Achieving this advancement would require heavy investments into research that spans the limitations described in this review. In addition to advancement in EHC technology, another area of research is the optimisation of mechanical compressors. This explores improvements in thermal management, embrittlement-resistant materials, seal and valve durability, and designs that minimise exergy destruction. There is also emerging research into hybrid electrochemical–mechanical compression architectures, all ultimately aimed to reduce operational energy demand in the high-pressure hydrogen space. The demand for efficacy in hydrogen compression is increasingly high as successfully overcoming these challenges would greatly favour the hydrogen energy market, creating a more sustainable approach to energy consumption than fossil fuels. Therefore, through a shared thermodynamic lens, this review highlights the latent potential of electrochemical hydrogen compressors, regardless of mechanical compressors' current superiority. It advises high investment into EHC research to unlock this potential and move towards a more energy-conscious, cost-efficient future.

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CONFLICT OF INTEREST

The author declares no conflicts of interest related to this work.

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