At the cathode, oxygen reduction ($\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$) proceeds on Pt-based catalysts. The open-circuit voltage (OCV) is described by the Nernst equation and decreases with temperature and with partial-pressure deviations from standard states.

Practical fuel cells operate below the reversible voltage due to polarization losses: (i) activation overpotential at both electrodes, (ii) ohmic losses through the membrane/electrodes/interconnects, and (iii) mass-transport limitations at high current densities. The resulting V–i curve exhibits a kinetic region, a quasi-linear ohmic region, and a concentration-loss region. Water management (avoiding membrane dry-out and cathode flooding) and thermal control are decisive for stable output.

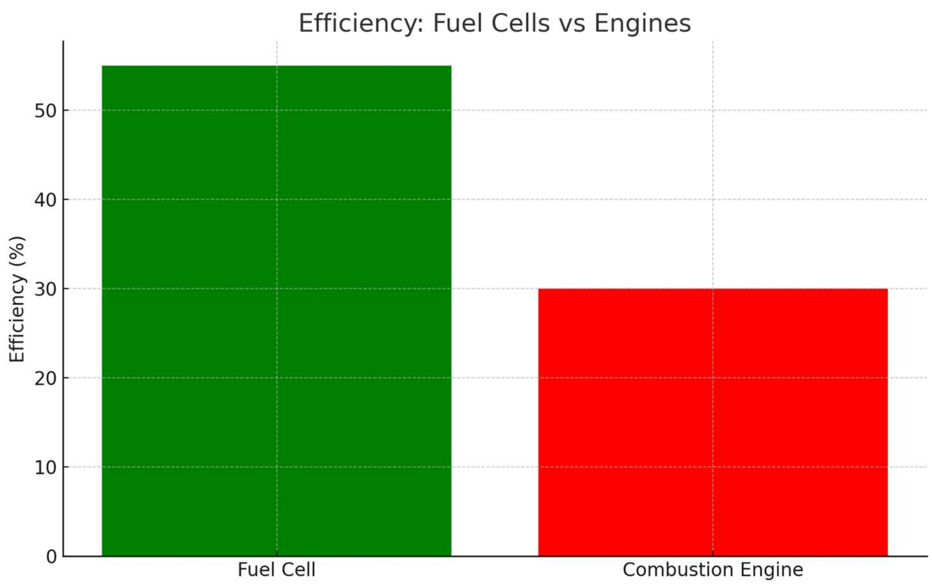



Figure 3. Illustrative efficiency comparison between fuel cells and heat engines.

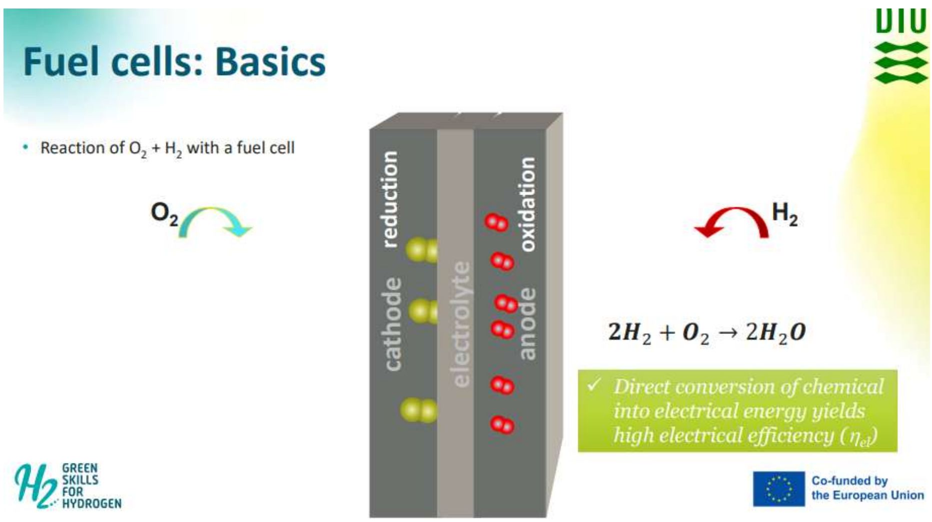
## 6. Components, Materials, and Degradation

Anode/Cathode: Gas-diffusion electrodes incorporate a porous carbon support, Pt-based nanoparticles, and an ionomer binder to create triple-phase boundaries for charge transfer. Catalyst loading and dispersion strongly influence activity and durability.

Electrolyte: PEMs (e.g., Nafion) conduct protons when hydrated; conductivity depends on water content and temperature. High-temperature membranes and reinforced composites seek improved tolerance to impurities and broader operating windows.

Bipolar plates & seals: Graphite, coated metal, or composite plates provide current collection and gas management channels. Elastomeric gaskets maintain sealing under thermal and humidity cycling.

Degradation: Mechanisms include Pt agglomeration/dissolution, carbon corrosion, membrane chemical/mechanical attack, and contaminant poisoning (CO, sulfur). Lifetime targets for vehicles exceed 5,000–8,000 operating hours; for stationary systems 20,000–40,000 hours are common benchmarks.




**Principle diagram of hydrogen fuel cell**

## 7. Storage, and Safety

Storage options include compressed gas (350/700 bar), liquid hydrogen (~20 K) with boil-off management, and solid-state storage (metal hydrides, chemical carriers like LOHCs). System selection trades volumetric/gravimetric density, cost, and response dynamics. Safety frameworks address leak detection, ventilation, and deflagration risk mitigation.

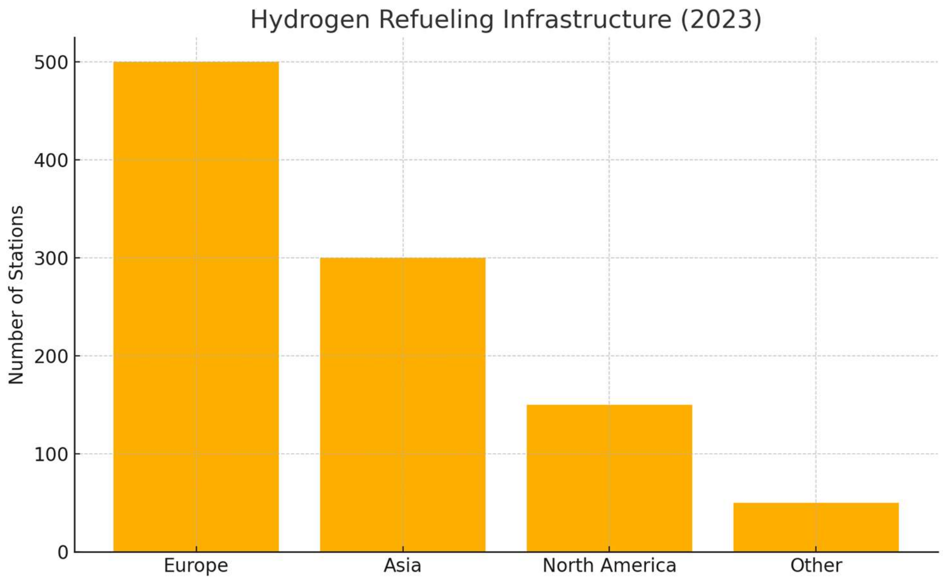
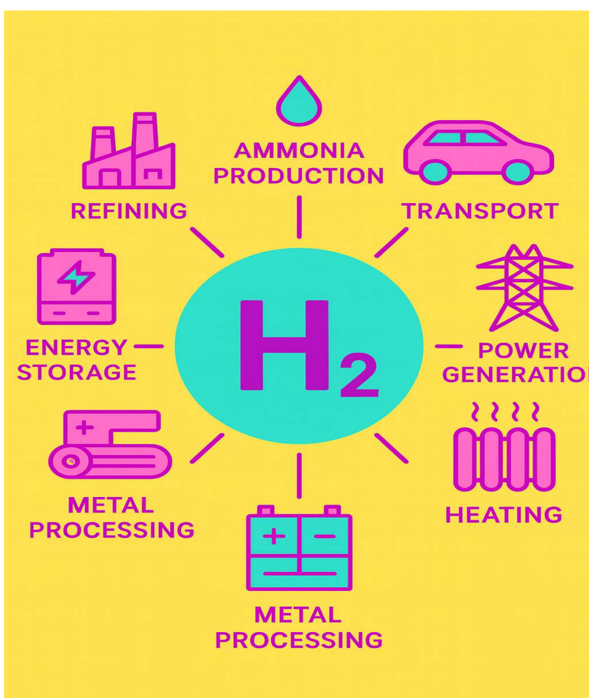



Figure 4. Indicative hydrogen refueling infrastructure by region (illustrative counts).

## Uses of hydrogen gas



## Outlook and Conclusions

Hydrogen fuel cells align with deep decarbonization needs where batteries are weight-constrained or where duty cycles favor fast refueling and continuous power. Continued R&D in catalysts and membranes, scaled manufacturing, and build-out of low-carbon hydrogen supply and infrastructure are the pillars of near-term progress.

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