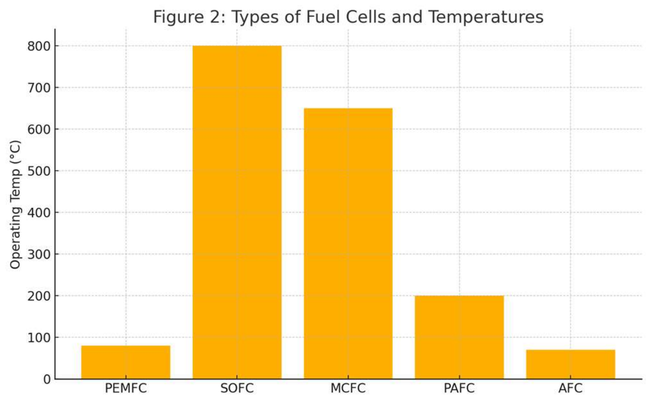
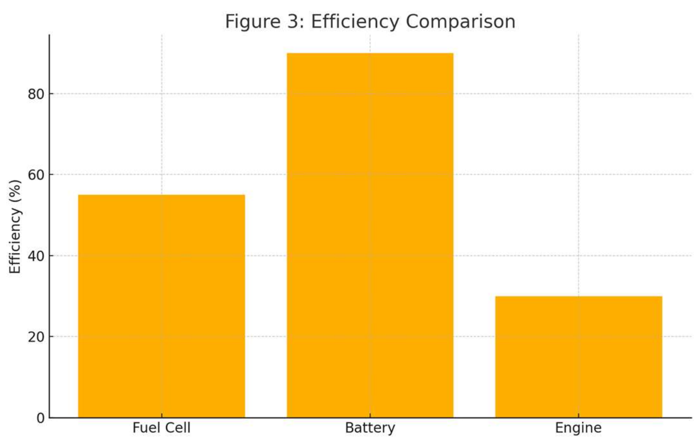
2: Fuel cell types and typical operating temperatures.



: Efficiency comparison between fuel cells, batteries, and engines.

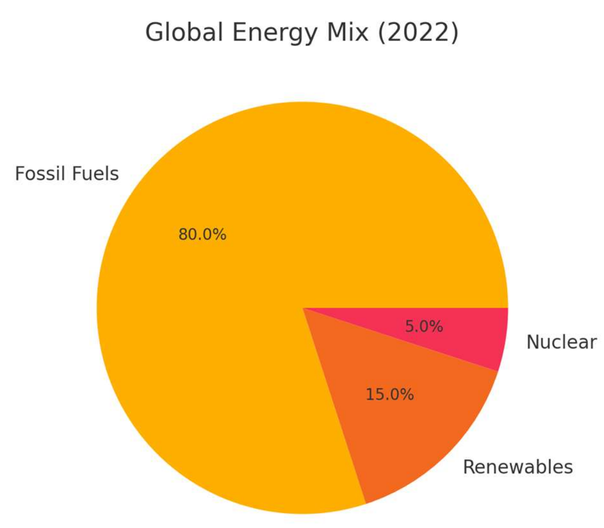


This image illustrates the main sources of hydrogen production, classified by color codes. Green hydrogen is produced using renewable energy like wind, solar, and water electrolysis. Blue hydrogen comes from natural gas with carbon capture technology. Gray hydrogen is also made from natural gas but without capturing emissions, leading to high CO_2 release. Brown hydrogen is produced from coal gasification, making it the most polluting option. The colors represent both the source and the environmental impact of each method.

2. Global Energy Challenges

Fossil fuels (coal, oil, and natural gas) still supply over four-fifths of global primary energy. This composition drives approximately three-quarters of anthropogenic greenhouse gas emissions. Air pollutants associated with combustion—NOx, SOx, and fine particulates—impose major public-health burdens, with millions of premature deaths attributed to poor air quality each year.

From a security perspective, reserve and production concentrations create systemic vulnerabilities. Geopolitical events can propagate quickly through fuel markets, translating into price volatility and macroeconomic instability. Diversification via electrification, renewables, and hydrogen can mitigate these exposures over time.



Indicative global primary energy mix (2022).

3. Renewable vs. Non‑renewable Energy Sources

Non-renewable sources provide dispatchable, energy-dense fuels but with high lifecycle emissions and finite reserves. Renewables such as solar and wind are clean and increasingly cost-competitive; however, their intermittency elevates the value of storage and flexibility. Hydrogen produced via electrolysis during periods of surplus renewable generation can be stored seasonally and reconverted in fuel cells when needed.

	Non-renewable Energy Sources	Renewable Energy Sources
Source	Coal, Oil, Natural Gas, Nuclear	Solar, Wind, Hydropower, Geothermal, Biomass
Availability	Limited (finite reserves, depleting over time)	Virtually unlimited (naturally replenished)
Environmental Impact	High pollution, greenhouse gas emissions, acid rain, waste	Low emissions, environmentally friendly, sustainable
Cost Trend	Increasing (due to scarcity, extraction, geopolitical risks)	Decreasing (due to technology improvements & adoption)
Energy Density	High (especially fossil fuels and nuclear)	Moderate to variable (depends on weather & resources)
Reliability	Continuous, independent of weather (except nuclear accidents)	Variable, depends on natural conditions (sun, wind, water)
Carbon Emissions	High (except nuclear which has low direct CO_2)	Very low or near zero
Long-term Sustainability	Not sustainable, will eventually run out	Sustainable indefinitely
Examples of Use	Transportation fuels, electricity generation, heating	Electricity, heating, transportation (green hydrogen, EVs)

Table 1. High-level comparison of energy sources and system attributes.

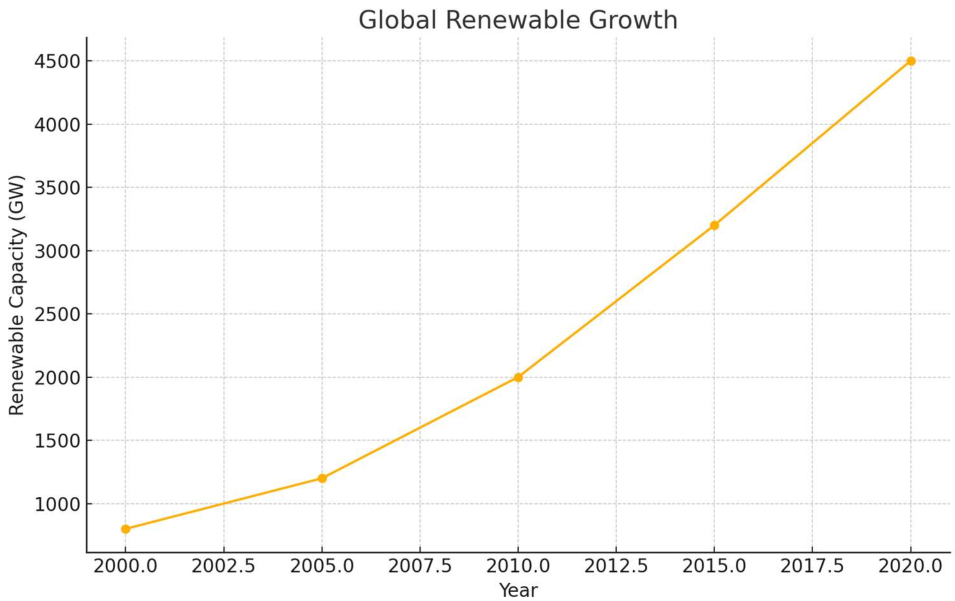


Figure 2. Trend in global renewable capacity (illustrative).

4. Definition and Historical Development of Fuel Cells

A fuel cell is an electrochemical device that continuously converts fuel and oxidant into electricity, heat, and reaction products. For hydrogen fuel cells, the overall reaction is hydrogen oxidation coupled with oxygen reduction to form water. Unlike batteries, the reactants are supplied externally, so power generation continues as long as fuel and air are provided.

Key milestones include Sir William Grove's 1839 'gas battery', mid-20th-century alkaline fuel cells powering NASA's Apollo missions (providing both electricity and potable water), and recent commercialization efforts in mobility, stationary cogeneration, and backup power.

5. Electrochemistry and Thermodynamics of PEM Fuel Cells

At the anode, molecular hydrogen is dissociatively adsorbed and oxidized to protons and electrons ($H_2 \rightarrow 2H^+ + 2e^-$). Protons migrate through a hydrated polymer electrolyte membrane (e.g., perfluorosulfonic acid), while electrons traverse the external circuit to deliver useful work before recombining at the cathode.