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# Retrofitting for Hydrogen as a Fuel

## PEP Report 32H


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## Glossary

| | |
|---|---|
| $/t | Dollars per metric ton |
| %wt | Weight percent |
| API | American Petroleum Institute |
| APS | Atmospheric plasma spray |
| ASME | American Society of Mechanical Engineers |
| atm | Atmospheres |
| ATR | Autothermal reforming |
| Bcm | Billion cubic meters |
| BFD | Block flow diagram |
| BLEVE | Boiling liquid expanding vapor explosion |
| BLI | Battery limits investment |
| BOP | Balance of plant |
| Btu | British thermal units |
| Btu/scf | British thermal units per standard cubic feet |
| °C | Degree Celsius |
| CCS | Carbon capture and storage |
| CCGT | Combined-cycle gas turbine |
| CCPP | Combined-cycle power plant |
| CEMS | Continuous emission monitoring system |
| CEMS | Emissions monitoring system |
| CF | Capacity factor |
| cf/ft$^3$ | Cubic feet |
| CHP | Combined heat and power |
| cm$^2$/s | Square centimeter per second |
| CNG | Compressed natural gas |
| cP | Centipoise |
| CS | Carbon steel |
| CTG | Combustion turbine-generator |
| dBA | A-weighted decibels |
| DLE | Dry low emissions |
| DLN | Dry low $NO_x$ |
| DOE | Department of Energy |
| EB-PVD | Electron beam-physical vapor deposition |
| EGR | Exhaust gas recirculation |
| EPA | Environmental Protection Agency |
| EPC | Engineering procurement construction |
| °F | Degree Fahrenheit |
| FECM | Fossil Energy and Carbon Management |
| FGR | Flue gas recirculation |
| FOB | Freight on board |
| Ft | Feet |
| Ft/s | Foot per second |
| g | Gram |
| G&A | General and administrative |
| GHG | Greenhouse gas |
| gpm | Gallons per minute |
| gr/L | Grams per liter |
| GT | Gas turbine |
| GREET | Greenhouse gases, Regulated Emissions, and Energy use in Technologies |
| GTCC | Gas turbine combined cycle |
| GTE | Simple-cycle gas turbine |
| GWh | Gigawatt hour |
| GWP | Global warming potential |
| h | Hour |
| HE | Hydrogen Embrittlement |

| | |
|---|---|
| HHV | High heating value |
| HP | High pressure |
| HRSG | heat recovery steam generator |
| HTHA | High Temperature Hydrogen Attack |
| HVOF | High-velocity oxy-fuel |
| ICE | International Electrotechnical Commission |
| IEA | International Energy Agency |
| IGT | Industrial gas turbine |
| IP | Intermediate pressure |
| IPA | Intermountain Power Agency |
| IR | Infrared |
| IRA | Inflation Reduction Act |
| ISO | International Organization for Standardization |
| J | Joules |
| K | Thousand |
| kg | Kilogram |
| $kg/m^3$ | Kilograms per cubic meter |
| kJ | Kilojoules |
| kPa | Kilopascals |
| kWh | Kilowatt hour |
| L | Liter |
| lb | Pound |
| LCOHS | Levelized cost of hydrogen storage |
| LHV | Lower heating value |
| LLNL | Lawrence Livermore National Laboratory (LLNL) |
| LNG | Liquefied natural gas |
| LP | Low pressure |
| LPPS | Low pressure plasma spray |
| $M^3$ | Cubic meter |
| mgal | Thousand gallons |
| MHPS | Mitsubishi Hitachi Power Systems |
| MJ | Megajoules |
| mJ | Millijoules |
| MJ/kg | Megajoules per kilogram |
| MJ/L | Megajoules per liter |
| Mlb | Thousand pounds |
| MMBtu | Metric million British thermal units |
| MMt | Million metric tons |
| MMt/y | Million metric tons per year |
| mol% | Molar percent |
| mPa | Megapascals |
| Mph | Miles per hour |
| MW | Megawatt |
| NEC | National Electrical Code |
| NETL | National Energy Technology Laboratory |
| NFPA | National Fire Protection Association |
| NG | Natural gas |
| OEM | Original equipment manufacturer |
| PEP | Process Economics Program |
| PFD | Process flow diagram |
| PNNL | Pacific Northwest National Laboratory |
| POX | Partial oxidation |
| ppb | Parts per billion |
| ppm | Parts per million |
| ppmv | Parts-per-million volume |
| PSA | Pressure swing adsorption |
| psi | Pounds per square inch |

| | |
|---|---|
| psia | Pounds per square inch absolute |
| psig | Pounds per square inch gauge |
| PSR | Perfectly stirred reactors |
| PTC | Production tax credits |
| RES | Renewable Energy Sources |
| ROI | Return on investment |
| RTE | Radiative transfer of energy |
| s | Second |
| scf | Standard cubic feet |
| scm | Standard cubic meter |
| SCR | Selective catalytic reduction |
| SHASTA | Subsurface Hydrogen Assessment Storage and Technology Acceleration |
| SMR | Steam methane reforming |
| SNCR | Selective noncatalytic reduction |
| SNL | Sandia National Laboratories |
| SPS | Suspension plasma spray |
| t | Metric ton |
| t/y | Metric tons per year |
| TBC | Thermal barrier coating |
| TFC | Total fixed capital |
| TWh | Terawatt hour |
| UGS | Underground natural gas storage |
| UHS | Underground hydrogen storage |
| USGC | United States Gulf Coast |
| UV | Ultraviolet |
| VGV | Variable geometry guiding vanes |
| vol% | Volume percent |
| VPS | Vacuum plasma spray |
| w/w | Weight for weight |
| WI | Wobbe Index |
| WLE | Wet low emissions |
| y | Year |

# Abstract

One crucial aspect of hydrogen is its role in decarbonization efforts. However, once produced, hydrogen requires storage if it is not utilized on-site. This report will consider hydrogen's use as a substitute fuel for refinery process furnaces and gas turbines, as well as explore current research into underground hydrogen storage options.

Using hydrogen as a replacement for natural gas poses several technical challenges. Hydrogen has only one-third of the volumetric energy content of natural gas, leading to concerns about fugitive losses. Material in contact with hydrogen must be considered since hydrogen embrittlement can occur. Additionally, its higher flame temperature results in increased $NO_x$ emissions. Safety considerations are also paramount; hydrogen's wider explosion range, lower ignition temperature, and tendency to form gas pockets at the top of enclosures all warrant careful attention.

This report will delve into these issues, addressing the requirements and potential challenges of retrofitting natural gas-fed systems for hydrogen use. We will specifically examine the integration of hydrogen into operations, including analyses of the capital and operating costs associated with retrofitting typical refinery furnaces and using hydrogen in gas turbines. Additionally, the report will cover hydrogen storage methods, with a focus on the economics of underground storage.

It is important to note that this report does not consider any clean hydrogen production tax credits (PTC) or credits for $CO_2$ avoidance. Under Section 45V of the Inflation Reduction Act (IRA), a clean hydrogen PTC allows up to $3/kg ($1.36/lb) of hydrogen produced for projects that achieve a life cycle greenhouse gas emissions intensity of less than 0.45 kg per kilogram of hydrogen.

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