# PEM Fuel Cell Technology - the best choice for fuel cell powered vehicles

**IQPC Conference:**
**F-Cells Infrastructure**

**Sean Casten**
**Peter Teagan**
**Richard Stobart**

Arthur D. Little, Inc.
Acorn Park
Cambridge, Massachusetts
02140-2390

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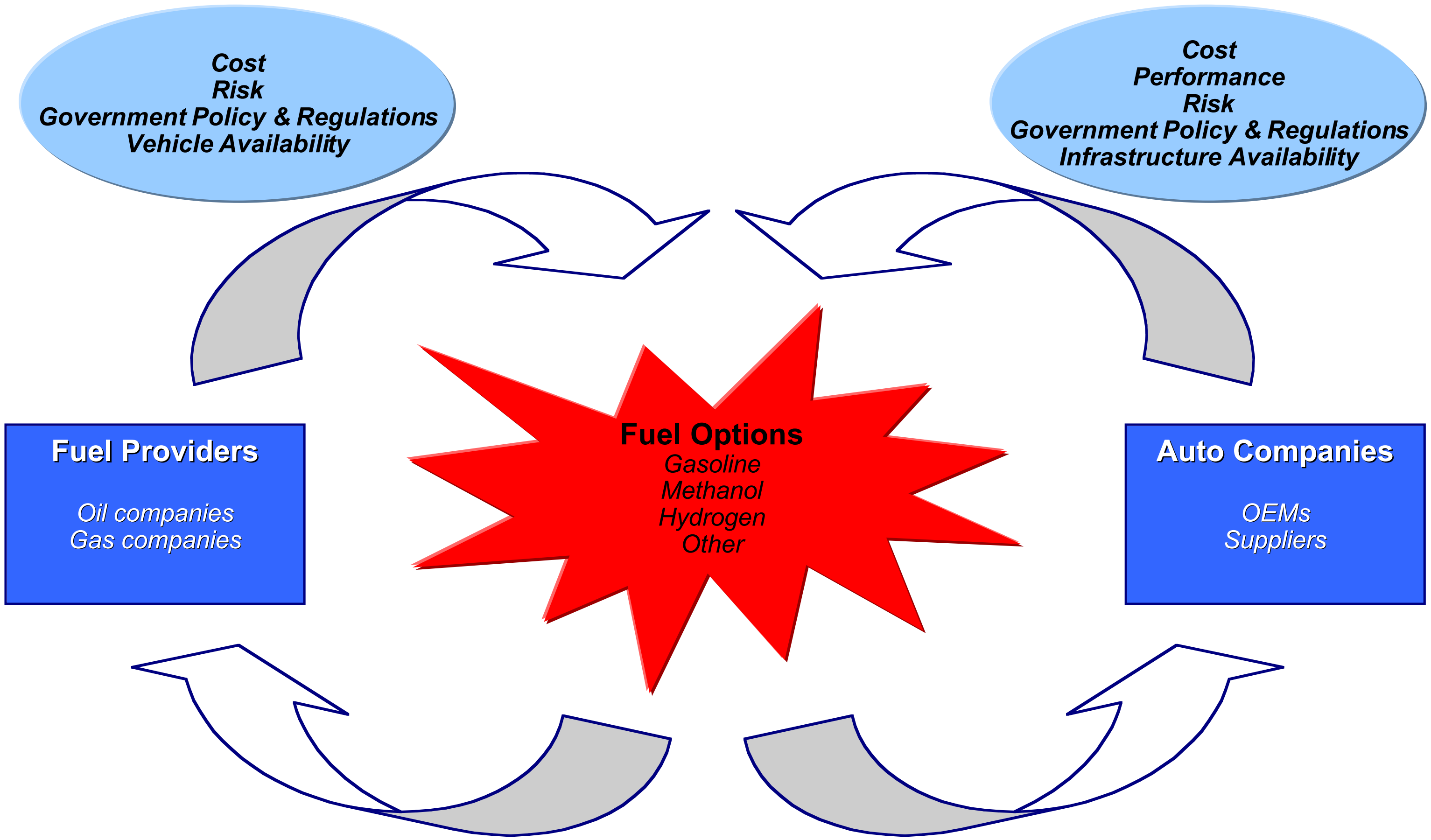
# Selection of the fuel for fuel cell-powered vehicles will require an intricate balance between fuel and vehicle suppliers.



# PEMFC technology has been pursued most actively for automotive applications by virtue of its small stack size and rapid start-up time.

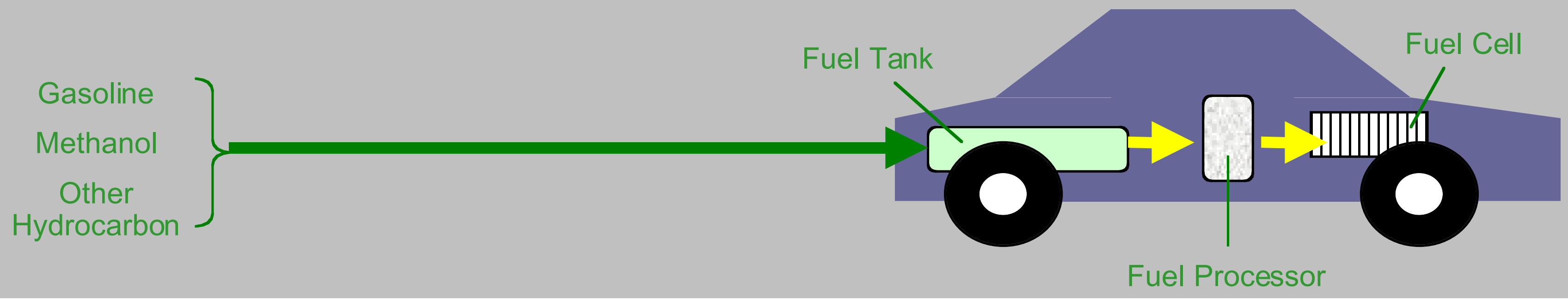
| Fuel Cell Technology | Peak Power Density* | System Efficiency (% HHV) | Start-up Time* (hours) |
|---|---|---|---|
| PAFC | ~200 mW/cm$^2$ | 36-45 | 1-4 |
| MCFC | ~160 mW/cm$^2$ | 43-55 | 5-10 |
| SOFC (tubular) | 150 - 200 mW/cm$^2$ | 43-55 | 5-10 |
| SOFC (planar) | 200 - 500 mW/cm$^2$ | 43-55 | unknown |
| **PEMFC** | ~700 mW/cm$^2$ | 32-40 | <0.1 |

* Values listed are for the fuel cell stack only, and do not include the reformer or other BOP.

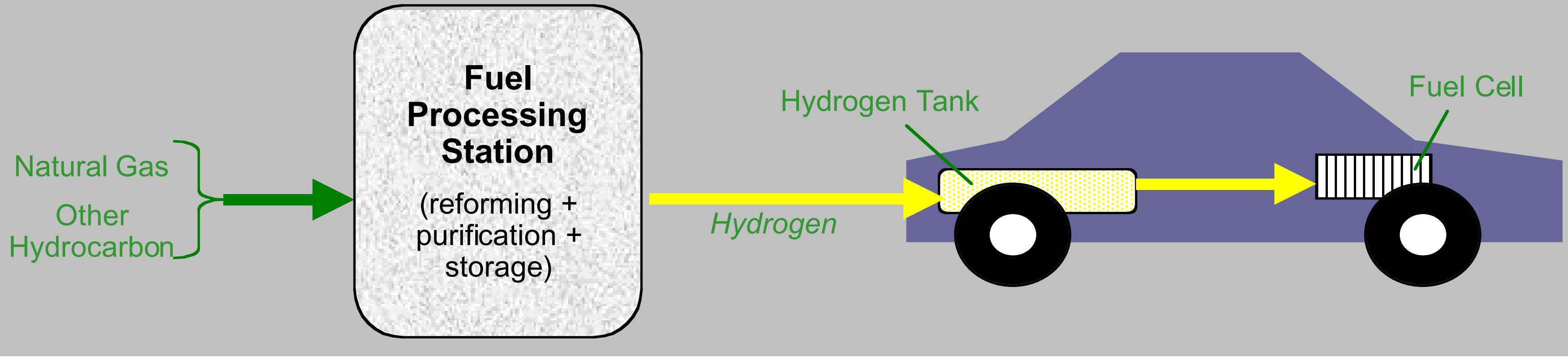
## The intolerance of PEMFC to fuel impurities (particularly CO) mandates that a fuel processor be present upstream of the FC stack.

This creates two broad options for FCV architectures:

**1. On-Board Reforming**




**2. Direct Hydrogen: (Reforming off the Vehicle)**




**Each approach has a unique infrastructure requirement.**

# The requirement for upstream reforming implies that there are four general fueling options that can be considered for FCVs.

## Off-board Options

**Central Merchant Hydrogen**

A large central plant produces hydrogen from natural gas or electrolysis, which is then transported over the road to hydrogen dispensing stations

**Local Electrolyzer / Fueling Station**

A hydrogen refueling station with on-site electrolysis, compression and dispensing equipment

**Local Reformer / Fueling Station**

A hydrogen refueling station with on-site natural gas reformer, compression and dispensing equipment

## On-board Options

**On-board reformer**

Hydrogen rich gas is produced from liquid fuels on-board the vehicle via a partial oxidation-, steam- or autothermal-reformer

# The central merchant hydrogen option will be difficult to implement in the near term on a large scale because of its infrastructure challenges.

## Off-board Options

**...al Merchant Hyd...**

A large centra... ...uces hydrogen from n... ...which is ...ported ov... ...drogen dispensing sta...

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## On-board Options

**On-board reformer**

...rich gas is produced from ...rd the vehicle via a ...autothermal-

- Common in small-scale fleet demonstrations
- Large-scale implementation implies significant infrastructure for $H_2$ distribution
- Unresolved codes and standards for hydrogen storage, transport and use favor generating hydrogen as close to end user as possible

# The local electrolyzer option will be difficult to implement in the near term on a large scale because of its economic challenges.

| Off-board Options | On-board Options |
|---|---|
| **[redacted]l Merchant Hyd[redacted]**<br>A large centr[redacted]uces hydrogen from n[redacted]which is [redacted]ported ove[redacted]drogen dispensing sta[redacted] | **On-board reformer**<br>Hydrogen rich gas is produced from liquid fuels on-board the vehicle via a partial oxidation-, steam- or autothermal-reformer |
| **[redacted]rolyzer / Fu[redacted]**<br>A hydrogen [redacted]n with on-site el[redacted]resse[redacted]sing equipment | |
| **Local Reformer / Fueling Station**<br>A hydrogen refueling station with on-site natural gas reformer, compression and dispensing equipment | |

- Producing hydrogen that is competitive with \$0.90/gallon gasoline (pretax basis) on a \$/mile driven basis will require electricity costs of <7 ¢/kWh[1] for electrolysis alone
- This does not include electricity requirements for compression, capital costs or other operating costs.
- US average commercial electricity rates are 7.4 ¢/kWh[2]

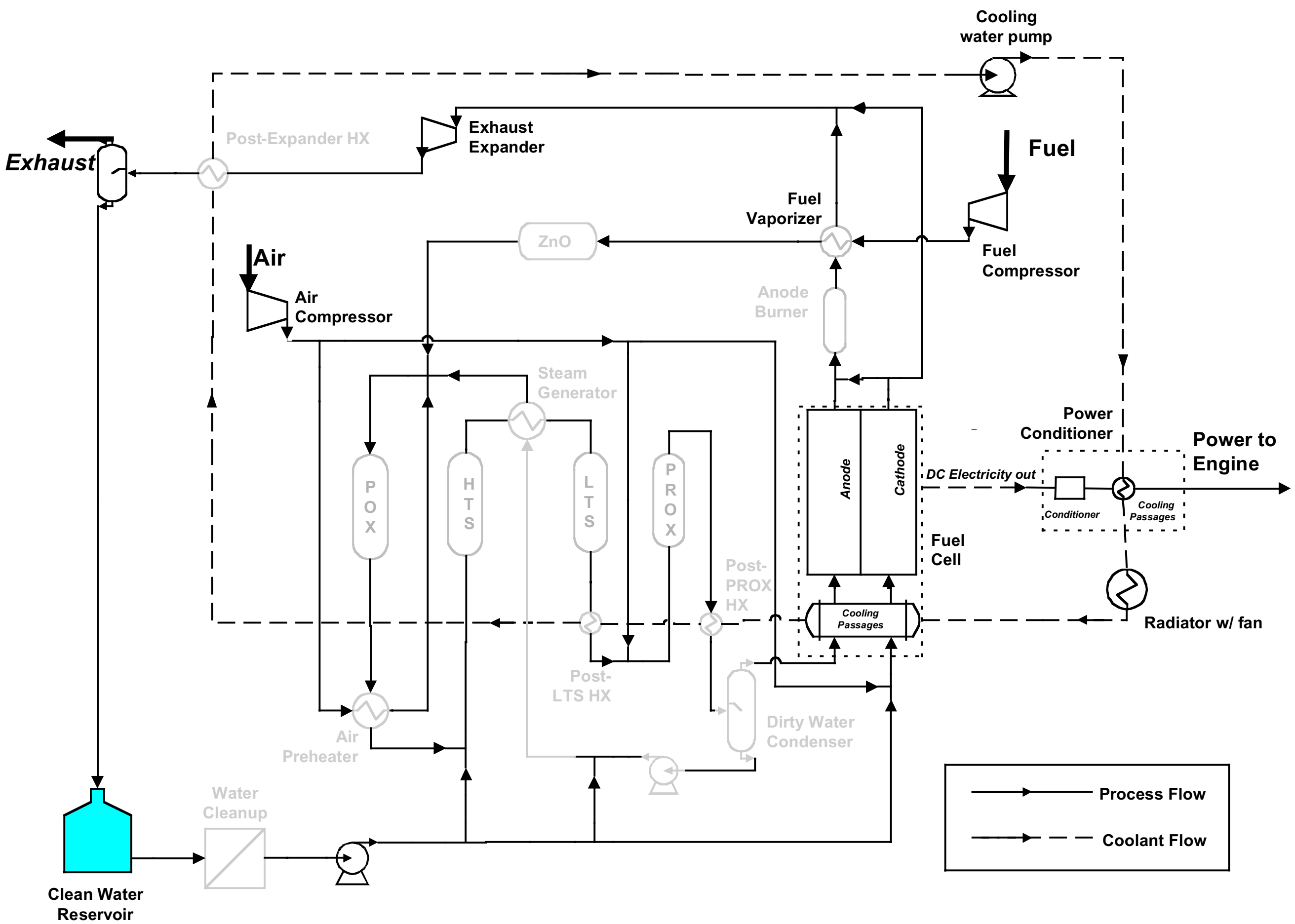
[1] Based on \$1.20/gallon gasoline, 27 mpg for conventional vehicles, 90 mpg gasoline-equivalent for $H_2$-fueled FCVs and 80% electrolyzer efficiency.

[2] DOE Energy Information Administration, 1998 data, representing a range of 5.0 - 12.3 ¢/kWh.

# This leaves two reasonable possibilities for the fueling of fuel cell vehicles, each with unique challenges and opportunities.

| | On-board Reformer | Local Reformer/Fueling Station |
|---|---|---|
| **Reformer Issues** | ¥ Multiple technologies available (SR, ATR, POX)<br>¥ No overwhelming cost or efficiency advantage to any | ¥ Multiple technologies available (SR, ATR, POX)<br>¥ No overwhelming cost or efficiency advantage to any |
| **Fuel Cell Issues** | ¥ Dilute hydrogen stream at anode implies <100% hydrogen utilization.<br>¥ Dilute hydrogen stream at anode implies reduced current density at a given voltage.<br>¥ CO control device required (PROX, etc.) | ¥ Pure hydrogen fuel maximizes fuel cell performance, minimizes fuel cell cost |
| **Fuel Choice Issues** | ¥ SR favors methanol fuel<br>¥ POX/ATR can be designed for operation on many hydrocarbon fuels including gasoline, ethanol, methanol. | ¥ Natural gas favored for reformer fuel<br>¥ Hydrogen fuel for fuel cell vehicle. |

# Fueling strategies including off-board reforming can significantly reduce the complexity on-board the vehicle...

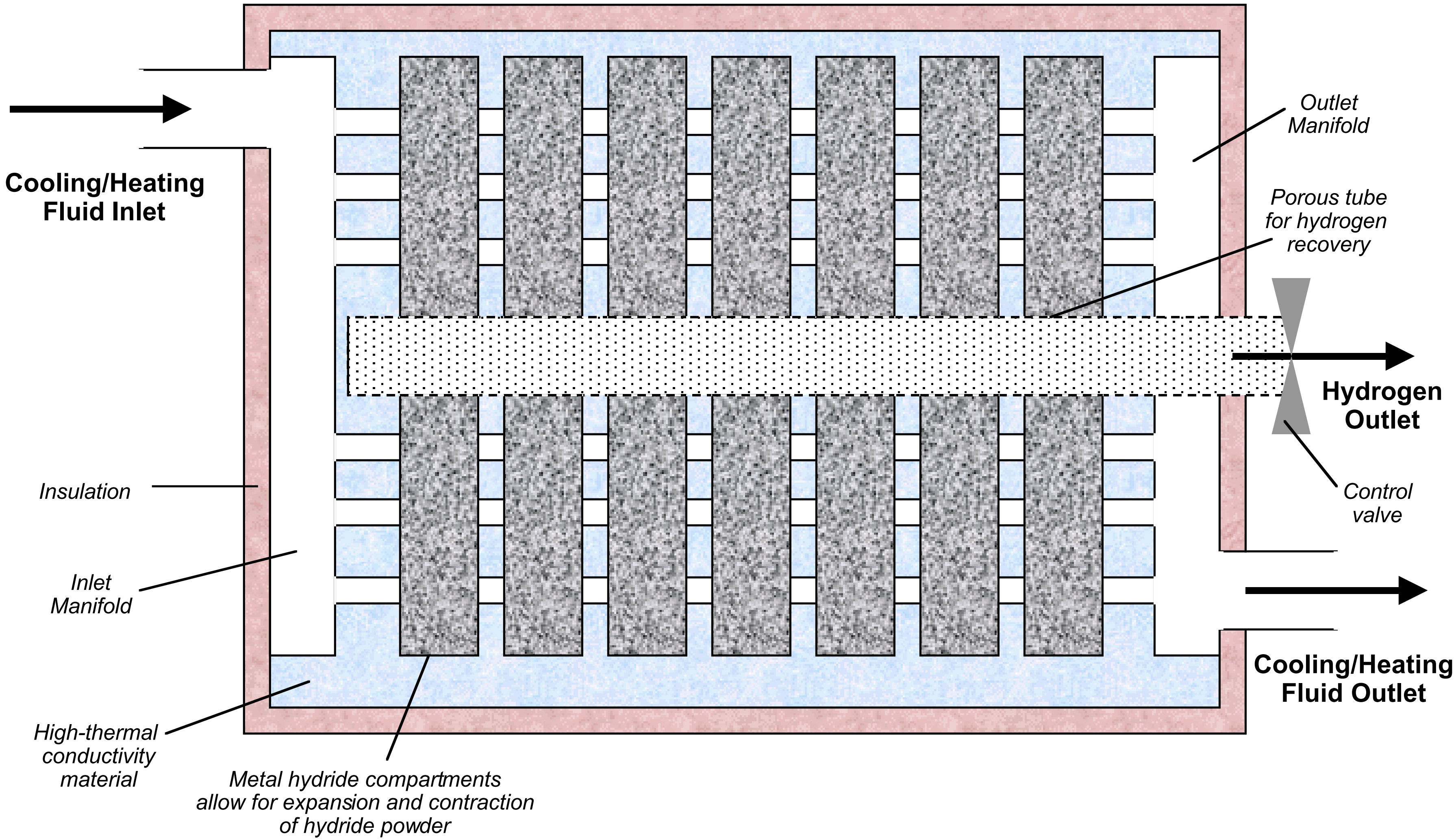



Items in **black** are required by systems with on-board reforming or direct hydrogen fueling
Items in gray are required only by systems with on-board reforming.

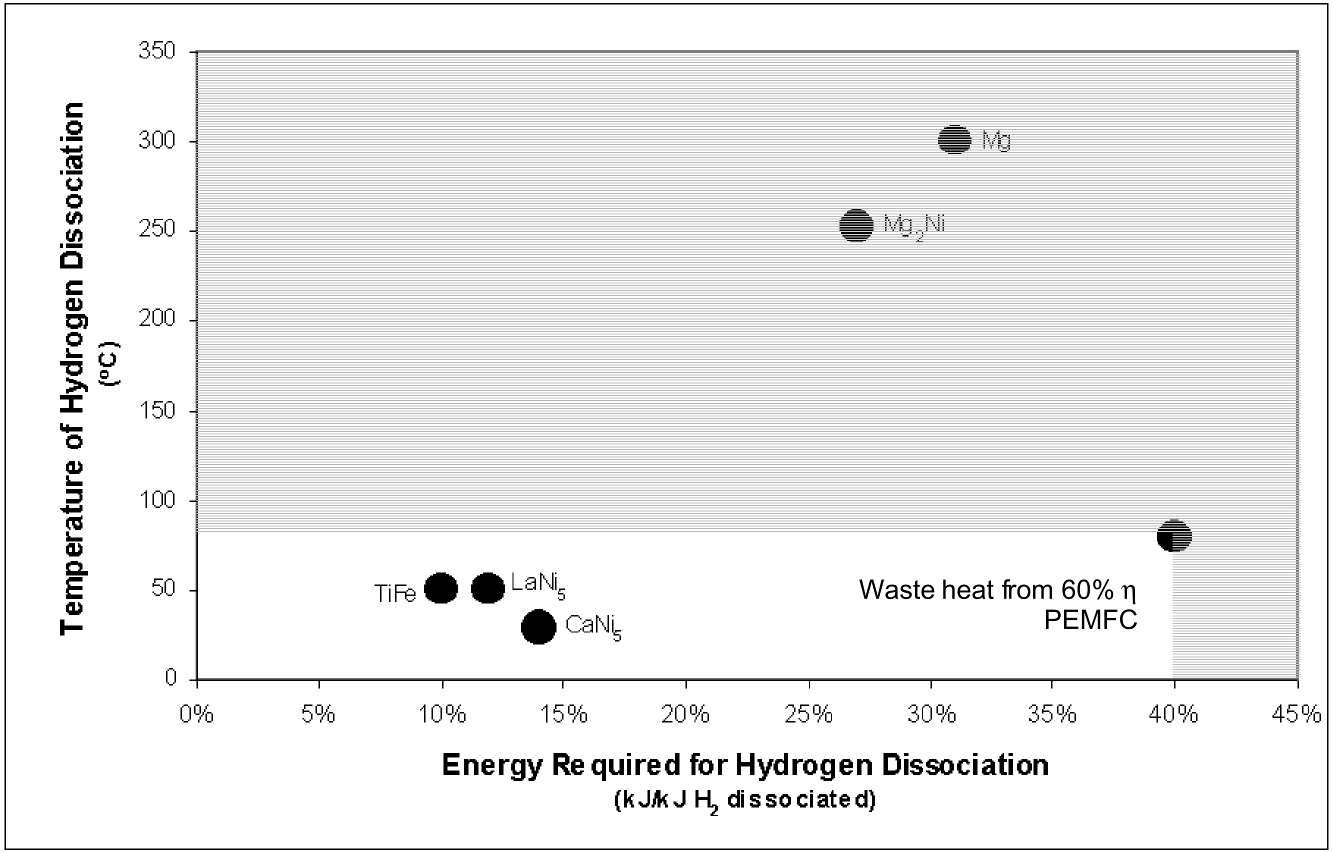
## but introduce complex ity both off *and* on-board the vehicle for hydrogen storage.

| Hydrogen Storage Alternatives | |
|---|---|
| **Storage Technology** | **Comments** |
| **Compressed Hydrogen** | ¥Successfully demonstrated in the Ballard bus (Chicago) and Ford P2000 prototype.<br>¥Requires storage pressures of 5,000 psi or greater for adequate range (compare to CNG pressures of 3,600 psi).<br>¥Compressor power requirements amount to 4 - 5% of the energy content of the hydrogen thus compressed.<br>¥Significant safety/design challenges remain for pressurized hydrogen storage |
| **Liquefied Hydrogen** | ¥Successfully demonstrated in the DaimlerChrysler NECAR 4.<br>¥Power requirements for liquefaction are approximately 23% of the energy content of the hydrogen thus liquefied.<br>¥Significant safety/design challenges remain for liquefied hydrogen storage |
| **Metal Hydrides** | ¥Storage of hydrogen at low pressure in a solid phase minimizes the safety risk associated with hydrogen storage, and reduces the energy requirements for pressurization<br>¥Thermal management of metal hydrides adds on-board complexity.<br>¥Thermal requirements for hydrogen dissociation limit the range of hydride technologies that can be realistically considered for PEMFC-based vehicles. |

# Metal hydride storage systems must allow for thermal and pressure management.



# The low operating temperature of PEMFCs limits the number of metal hydride formulations that may be used in fuel cell vehicles.



# Compressed hydrogen fueled FCVs represent the lowest near-term cost option for fuel cell vehicles.

| | Powertrain-only cost as a function of range | | Comments |
|---|---|---|---|
| | 250 km | 500 km | |
| On-board reforming | | | • Upper end of cost range more likely in near term. |
| Fuel tank | $33 | $57 | |
| Reformer | $900[a] - $3,000 | $900[a] - $3,000 | |
| Fuel cell | $1,750[a] - $5,000[a] | $1,750[a] - $5,000[a] | |
| **Total[b]** | **$2,700 - $8,000** | **$2,700 - $8,000** | |
| Pressurized $H_2$ | | | • Fuel cell costs will be lower than reformer-based systems due to higher hydrogen utilization and higher current densities. |
| Tank | $900 | $1,500 | |
| Fuel cell[1] | $1,750[a] - $5,000[a] | $1,750[a] - $5,000[a] | |
| **Total[b]** | **$2,650 - $5,900** | **$3,250 - $6,500** | |
| Metal Hydrides | | | • Hydride system costs based on Toyota's TiCrV material.<br>• Fuel cell costs will be lower than reformer-based systems due to higher hydrogen utilization and higher current densities. |
| Hydride system | $2,300 - $3,600 | $4,600 - $7,200 | |
| Fuel cell | $1,750[a] - $5,000[a] | $1,750[a] - $5,000[a] | |
| **Total[b]** | **$4,000 - $8,600** | **$6,400 - $12,200** | |

[a] Based on long-term PNGV goals for a 50 kW powertrain.

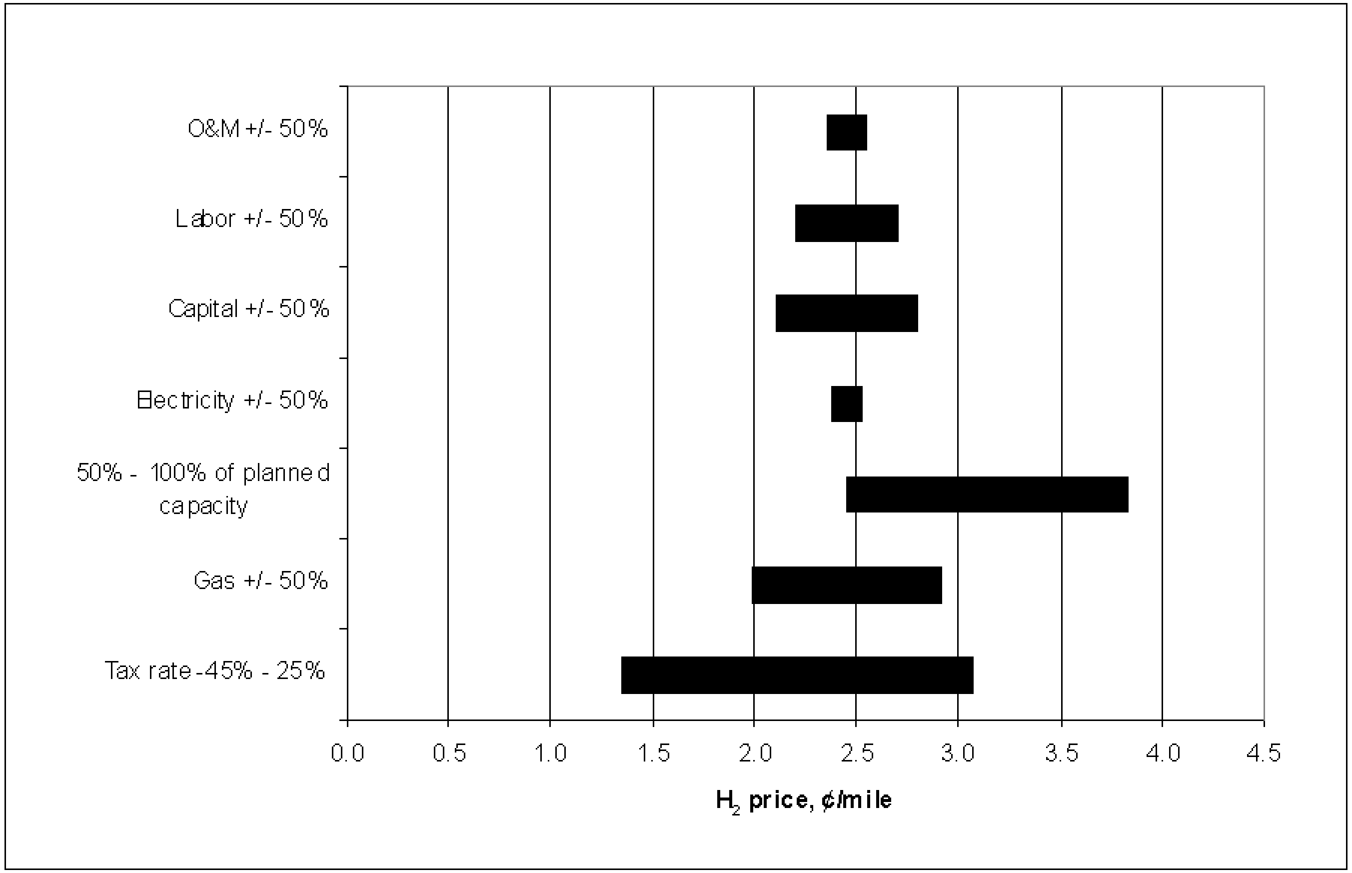
[b] For primary drivetrain subsystems - does not include balance of plant components (air handling, transmission, etc.) or components that are common (e.g., power electronics) among all systems.

# The production costs of hydrogen in a local reformer/fueling station could be competitive with gasoline on a $/mile driven basis.

| Expense Item | Cost ($/GJ $H_2$) | Comments |
|---|---|---|
| Electricity Cost | $1.09 | Assumes 6 ¢/kWh |
| Gas Cost | $6.47 | Assumes 4 $/MMBTU |
| Reformer O&M | $0.43 | Assumes 10% of capital cost |
| PSA O&M | $0.38 | Assumes 10% of capital cost |
| Compressor system O&M | $0.03 | From literature estimates of Ogden, et al. |
| Labor | $3.40 | Assumes 3 employees at $50,000/year total labor cost |
| Annual capital charge | $3.88 | Annual cost = 15% of total capital cost |
| Markup (profit, marketing, etc.) | $0.97 | 25% of capital cost |
| Total $/GJ | $17.14 | Does not include tax. |
| **Hydrogen FCV ¢/mile before tax** | **2.3** | Assumes $H_2$-FCV attaining 91 mpg gasoline equivalent |
| Compare: $/GJ for gasoline | $6.92 | Assumes $0.90/gallon, 130 MJ/gallon: does not include tax |
| **Gasoline ICEV ¢/mile before tax** | **3.0** | U.S. Tax is approximately 25% of total fuel cost |

All values are based on ADL analyses, unless otherwise noted at production volumes of 100 units/year.

## Sensitivity analyses show that the deviation from planned capacity has the most significant impact on the cost of delivered hydrogen.




**This has implications on the overall risk of hydrogen delivery for fuel providers.**

## Successful commercialization strategies for fuel cell vehicles will have to involve the auto and fuel industries.