The fuel

Hydrogen does not exist naturally in any useful quantities. It must be extracted from a feedstock compound. The two most convenient feedstocks are water and hydrocarbons such as coal, petroleum, and natural gas.

In order to liberate the hydrogen from an exceptionally stable molecule such as water, one must expend significant amounts of energy to liberate it - more energy than can ever be extracted from the hydrogen when re-combined with oxygen during combustion or within a fuel cell. Electrolysis efficiency on an industrial scale is estimated to be capable of 80-94% efficiency, with that upper figure requiring rather costly equipment.

Freeing hydrogen from a less stable molecule such as methane or some other hydrocarbon via steam reformation requires less energy than electrolysis, but is still a net energy loss and generally produces carbon dioxide.

Once you have have freed hydrogen from its feedstock, you then have the challenge of containing it. Hydrogen is the lightest molecule with an average atomic weight of 2 *(most hydrogen is absent a neutron in its nucleus)*. As such the molecules are rather energetic and a cubic meter of hydrogen at STP has about one third the net energy of a cubic meter of natural gas. As a light and energetic molecule, it can not only penetrate the best gas seals with depressing ease, it can literally diffuse through any solid material including rather dense steel. This process wears out seals, containment vessels, and fittings at an alarming rate.

In order to store or transport any useful quantity of hydrogen, one must either compress it to great pressures of 5000 PSI *(or greater!)*, or refrigerate it down to about 20 degrees *kelvin* so it condenses into a conveniently energy-dense liquid. The energy required to compress hydrogen to 5000 PSI represents about 20% of the energy content of the hydrogen itself; refrigerating it to 20K around 40% of the hydrogen's net energy content. Neither 5000 PSI-capable compressors nor 20K-capable refrigerators are particularly efficient near the extremes of their operating ranges, so the 20% and 40% net energy penalty figures are rather optimistic.

There has been much excitement about the possibility of using a metal hydride to store hydrogen in an energy-dense format without the problems of compression and liquefaction, but no practical results have surfaced. Indeed, the only really successful use of hydrogen stored in metal hydrides are mundane nickel-metal hydride (NiMH) and the more exotic nickel-hydrogen (NiH) battery types.

The cars

Fuel cells are very expensive things to build. The one-off and short production run fuel cell stacks used in demonstration FCVs all cost in excess of *one million dollars* apiece to build - and that's only covering the raw materials and labor to fabricate each stack. Volume production of fuel cells is expected to bring the cost down to about $7,000 per kilowatt - hardly affordable when the average car requires anywhere from 50 - 100kW of power to the wheels to achieve good "highway onramp" performance, nevermind the 0-60 figures that sell cars these days. The reality is that while automotive fuel cell stacks have recently been announced that can achieve around 75kW of rated power, like engines they have "parasitic" loads that reduce their real-world performance. These loads cut into fuel cell margins even more than engines to the point that a 75kW faceplate rating will likely result in less than 50kW to the wheels.

Running the numbers yields an optimistic cost of $700,000 for a 100kW rated fuel cell *(we're going to assume that's the cost for the whole shebang - fuel cell stack, associated support equipment, fuel storage, etc)*. Since very few can afford that kind of dough for transportation, let's say you take the hybrid-car route and spec out a 50kW unit and supplement it with a large-ish battery pack to handle the peak demand while the fuel cell works at greater than average demand to keep that pack reasonably well-charged. You might have dropped the cost of your stack by half, but that has also bought you a big battery pack that's hardly free. Thankfully, the electric motor that will be receiving all this energy is likely to be around 90% efficient.

A big part of the expense of fuel cells is tied up in the exotic materials they depend on. Decades of research has yet to eliminate the platinum catalysts that make them so costly to build.

The lifespan of fuel cells is also significantly less than the average engine. Under near-laboratory conditions, automotive fuel cell stacks are achieving mere thousands of hours operating life before their output drops off. In the real world where environmental conditions will vary greatly and the air being fed to the fuel cell will vary greatly, operational lifespan will be cut greatly. Given the sealed-assembly nature of fuel cells, it will be exceptionally difficult to repair them once their output begins to drop near end-of-life.

Remember the challenges of storing hydrogen? A 5000 PSI-rated steel tank weighs in at about 65 times the mass of the hydrogen it must contain and has to be spherical or some other strong *(and inconvenient)* shape such as a domed cylinder. Given that 1kg of hydrogen has approximately the same amount of energy as a gallon of gasoline. Given that a low-temperature hydrogen fuel cell can aspire to around 50% efficiency *(nearly double that of the average gasoline internal combustion engine)*, 10kg of hydrogen seems like a reasonable fuel capacity, resulting in a 650kg (1430lb) fuel tank. Given that carrying a fuel tank that weighs more than one third the average passenger car is likely going to be impractical, expensive carbon-fiber tanks weighing only 10 times as much as the hydrogen could be employed but they're not exactly crash-rated like steel, and the vehicle and its inhabitants are going to be vaporized in the event of a serious tank rupture.

If the FCV designer takes the liquid hydrogen approach, one would not necessarily need tanks as strong (or heavy) as a 5000 PSI compress-gas tank, but you have the problem of maintaining that 20K temperature. 20K is a mere 20 degrees above absolute zero and maintaining something close to that temperature requires some impressive insulation, constant energy input, or both. NASA uses a good deal of liquid hydrogen in the space program, and their storage tanks are impressive examples of "at any cost" design to the point that a cup of hot coffee placed in one of those tanks would stay hot for years. In the case of a motor vehicle, there just isn't the engineering (or financial) margin for either insulation of refrigeration, so your design must allow the hydrogen to "boil off" as it inevitably gets warmer (read: expands). All practical liquid hydrogen storage systems for automobiles must boil hydrogen at a rate that would leave a fully-fueled vehicle empty in just 2 weeks. Aside from the inconvenience and waste, this represents quite the safety hazard since hydrogen is explosive in relatively low concentrations.

There is always the option of going the cheap and easy route and just designing hydrogen-burning internal combustion engines. While far cheaper than a fuel cell, this approach is more difficult and expensive than converting a gasoline engine to run on natural gas, and hydrogen internal combustion engines are less thermally efficient than either because it simply burns too fast for conventional piston-engine designs to effectively capture the energy. The engines also wear out a good deal faster thanks to the very properties that make hydrogen so difficult to store. It's also inconceivable that anyone is going to go to all the expense to make hydrogen only to burn it at less-than-gasoline efficiencies.

The infrastructure and the economy

There are a number of proposed schemes for a "hydrogen economy," and none of them are particularly workable.

First, hydrogen must be produced at great expense in terms of capital equipment and energy. Electrolysis takes staggering amounts of electricity to the point that it likely can't compete with steam reformation of hydrocarbons which the petroleum industry already has limited capacity to perform.

Next, the hydrogen must be distributed. Pipelines won't work out so well since hydrogen is a tough gas to contain and will be exceptionally expensive to pipeline due wear on the pipelines, leakage, the high pressures necessitating beefier pipes, and the much greater energy needed to move it. The incredible mass of steel tanks will make it pointless to move via tanker truck - a mere 200kg of hydrogen is about all that a 13-ton tanker can move; crash-rated carbon-fiber tanks might happen, but the capital expense would be tremendous.

Finally, there's the point of retail distribution - likely something resembling a gas station. Assuming the hydrogen delivery problems have been resolved, there are the issues of staggering power consumption, capital expense, and safety. If the hydrogen is produced on-site, the power consumption and capital equipment expenses only go up.

A hydrogen station with hydrogen delivered from a refinery of some sort must posses a significant hydrogen storage facility capable of containing thousands of kilograms of the stuff at 5000 PSI or greater. It will also need some sort of compressor facility since the pressure in their tanks alone will not fill up an empty hydrogen tank. 5000 PSI-capable compressors and pipes/fittings/valves/etc are rather costly things to own. The storage facility would be a hazard of itself. Inspections and preventative maintenance would need to be constant. The people operating this facility would need a great deal of training.

If the hydrogen is produced on-site, the facility now needs to own an electrolyser or do onsite steam reformation. While it might be possible to do either efficiently in a handful centralized locations where volume can cover the capital burden, on a distributed basis the efficiency drops. Electrolysis is estimated to cost approximately 45kWH per kilogram assuming an 85% efficient electrolyser - meaning that a 10kg hydrogen fillup consumes 540kWH with the 20% compression penalty (assuming 100% compressor efficiency!). **That's $27 worth of electricity at $0.05/kWH!**

Given that gasoline station like "quick refueling" is touted as being a critical component of FCVs, **80.5kWH** of energy needs to be expended compressing 10kg of hydrogen. Assuming a leisurely fill up time of 6 minutes, that means that your compressor need a continuous **805kw** of power over those 6 minutes. That's more energy than the average power line feeding a residential neighborhood can deliver! The handful of production BEVs out there could go 200-800 miles on the energy required to compress the hydrogen alone!

When it's all said and done, it's completely impractical to perform any sort of retail "hydrogen distribution" assuming hydrogen priced anything near what gasoline and diesel go for today.

The cars themselves need to achieve a 500 factor drop in production costs to be cost-competitive with gasoline-powered cars.

The inescapable numbers

One kilogram of hydrogen contains roughly 35kWH of energy. For comparison, gasoline contains 33-39kWH of energy per gallon depending on formulation (we'll assume 36kWH since that seems to be the most common figure).

Real-world electrolysis takes 45kWH to make 1kg of hydrogen. Steam reformation is more efficient - let's say it only takes 41kWH.

If we assume our compression is 85% efficient, we're looking at a 23% compression penalty.

While fuel cells are roughly 50% efficient under ideal conditions, that is a rating of thermal efficiency, not operating efficiency. All fuel cells I've been able to get information on have 25-33% operating margins.

Say we're going to follow 10kg of hydrogen produced via steam reformation of methane start to finish.

- 410kWH of energy was expended to reform the methane into hydrogen congaing 350kWH of energy
- 80.5kWH of energy was expended compressing it to 5000PSI
- 175kWH (50%) of thermal energy was captured by the fuel cell
- 43.75kWH (25%) of energy was spent keeping the fuel cell running
- 157.5kWH (90%) was delivered to the wheels

Our 490.5kWH of energy input resulted in 157.5kWH to the wheels, **or an optimistic 32.11% cycle efficiency**.

In reality, efficiency would probably be much less with the biggest hit coming from thermal efficiency of the fuel cell being 40% (140kWH extracted, 45kWH overhead), cutting cycle efficiency to 21.4%.

So, instead of getting 20-30 MPG in the average gasoline-powered car, your FCV gets 40-60 MPG equivalent. Reducing that number to a more useful figure such as watt-hours per mile makes for easier comparison:

Miles per gallon	Watt-Hours per mile
10	3600
20	1800
30	1200
40	900
50	720
60	600

By comparison, highway-capable electric vehicles achieve anywhere from 400 WH/mile at the least efficient to around 100 WH/mile at the best.

Energy flow will be more like this for an electric car:

- 55kWH of electrical energy is delivered to the vehicle
- 49.5kWH (90%) of energy goes into the battery pack
- 44.5kWH (90%) was delivered to the wheels

Looks like we lost less than 20% of the "Wall-plug" energy with the EV for **80.9% cycle efficiency**.