Hydrogen; The Improbable Dream

The Dream

The web site of the Department of Energy continues to state that “The Central Mission of the United States Department of Energy Hydrogen Program is to research, develop, and validate fuel cell and hydrogen production, [transport], and storage technologies.”

Further, “Hydrogen from diverse domestic resources will then be used in a clean, safe, reliable, and affordable manner in fuel cell vehicles and stationary power applications.”

Finally, “Development of hydrogen energy will ensure that the United States has an abundant, reliable, and affordable supply of clean energy to maintain the Nation’s prosperity throughout the 21st century.”

The dream is a fantasy

This is the dream, the dream of a “hydrogen economy”, but it is, really, only a *fantasy*.

The main reason the dream is actually a fantasy is that *there is no hydrogen*. Whatever hydrogen there might have been at one time here on Earth is *all used up*. There is plenty of water, but water is used up, or “burnt” hydrogen.

To get the type of hydrogen that the fuel cell can “burn”, *elemental hydrogen*, we must first “unburn” the water. “Unburning” water to produce elemental hydrogen in order to burn it again is a losing proposition.

The two other big reasons that the “hydrogen economy” will remain a fantasy are the cost of *storage* of hydrogen, and the cost of *transport* of hydrogen.

Fuel

Let’s remember what a fuel is. A fuel is an energy source that *occurs in Nature*. Wood is a fuel; coal is a fuel; oil is a fuel; natural gas is a fuel. These forms of chemical energy, wood, coal, oil, and natural gas, *occur in nature*, and thus these materials are fuels.

In contrast, neither electricity nor elemental hydrogen is a fuel since neither occurs in useful form or amount in nature. Both electricity and elemental hydrogen must be made, and each must be *made from a fuel.*

Energy efficiency

When one form of energy is changed into another form of energy the "useful" energy that is produced by the change is less than the energy that is invested in the change. The efficiency of energy conversion is always less than one; energy efficiency is always *fractional.*

We can calculate this fraction, the energy efficiency, by dividing the useful energy that is produced by *all* the energy that is invested. The energy that is invested is the energy required by the process (energy of agency) *plus* the energy of the fuel that is consumed in the process (energy transformed).

$$\text{energy efficiency} = \frac{\text{useful energy produced}}{\text{energy of agency + energy transformed}}$$

We illustrate this relationship with a made-up example in which we say that the energy of agency and the energy transformed are equal.

energy of agency + energy transformed	⟶	useful energy produced
both together = 2 units of energy	**50% efficiency**	**1 unit of energy**

If no energy of agency were needed the useful energy produced would equal the energy transformed, and the efficiency would be 1. This, however, can never be true. The efficiency of energy conversion will always be less than 1, usually much less, and this is the reason that it will always be a losing proposition to "unburn" hydrogen so as to burn it again.

Electricity

While hydrogen is not the same as electricity, hydrogen and electricity are similar. Hydrogen, like electricity, must be made from a fuel, and the characteristics of production, transport, and storage of hydrogen are similar to those of electricity. Since electricity is more familiar than hydrogen we will summarize first the production, transport, and storage of electricity.

Making electricity

Most electricity, or *electrical energy*, is made by generating stations that burn a fuel such as coal, oil, or natural gas to produce steam at a high temperature and pressure. The hot steam then spins the turbines that run the electrical generators. A smaller amount of electricity is made by generating stations that use nuclear energy to make the steam for the steam turbines, and still smaller amounts of electricity are produced by water turbines (hydroelectric plants), and air turbines (wind “farms”).

The great virtue of electrical energy is its convenience. We need only flip a switch and the energy flows, but there is a cost to this convenience. The energy consumed in the production of electricity is about three times greater than the energy of the electricity that is produced. That is, the efficiency of the generation of electricity is about 35%.

Transporting electricity

We rarely consider the “transportation” of electricity, although we may be aware of electrical cords inside our houses, and of high-voltage lines and transmission towers out in the country. It turns out that energy is lost to resistance (friction) during the transmission of electricity, and this loss is great enough that electrical generating stations are typically built close to the point of consumption. It is cheaper and more efficient, for example, to haul many train loads of coal per day from Wyoming to power stations in Illinois than to produce the electricity in Wyoming and send it East by wire.

Storing electricity

Electricity is rarely stored. Most electricity is used as it is generated, but small amounts of electricity can be stored in batteries.

Hydrogen

We return now to hydrogen.

Making hydrogen

Since elemental hydrogen does not occur in nature here on Earth we must make it before we can burn it.

As we saw in the chapter on hydrogen, elemental hydrogen can be made by the reaction of steam with either methane or natural gas, by the reaction of steam with coal, and by the electrolysis of water.

Hydrogen from methane or natural gas

Hydrogen is produced in large quantity from methane and natural gas, which is mostly methane, by steam reforming followed by the water-gas shift reaction.

$$CH_4 + 2\ H_2O \xrightarrow[\text{water-gas shift}]{\text{steam reforming}} CO_2 + 4\ H_2$$

methane	**water**		**carbon dioxide**	**hydrogen molecules**
1.4 units of energy		**70% efficiency**		**1 unit of energy**

In the steam reforming of methane 1.4 units of other energy are required in order to make one unit of hydrogen energy (70% energy efficiency).

The overall energy efficiency cannot be estimated from the balanced chemical equation because the equation does not show the methane, or other fuel, that must be consumed to provide the energy of agency.

"Hydrogen from coal"

We saw also that hydrogen can be produced by treating red-hot coal with steam; by steam reforming followed by the water-gas shift reaction. As the equation indicates, most of the hydrogen actually comes from water.

$$C + 2\ H_2O \xrightarrow[\text{water-gas shift}]{\text{steam reforming}} CO_2 + 2\ H_2$$

coal	**water**		**carbon dioxide**	**hydrogen molecules**
2.3 units of energy		**35% efficiency**		**1 unit of energy**

In the reaction of steam with coal 2.3 units of other energy are required to make one unit of hydrogen energy (35% energy efficiency).

Hydrogen from electrolysis of water

The electrolysis of water can also produce hydrogen.

$$2\ H_2O \xrightarrow{\text{electrolysis}} 2\ H_2 + O_2$$

water		**hydrogen**	**oxygen**
1.4 units of energy	**70% efficiency**	**1 unit of energy**	

In the electrolysis of water 1.4 units of other energy are required to make 1 unit of hydrogen energy (70% efficiency).

While the energy efficiency of electrolysis could be increased by using a lower voltage, the rate of the reaction would be correspondingly reduced.

Limits to the efficiency of energy conversion

No process can have an energy efficiency greater than 1. With the exception of converting some other form of energy to heat, the efficiency of energy conversion can never equal 1. No amount of research or wishful thinking will change this fact of nature.

Energy efficiency in the manufacture of hydrogen

As we have just seen, the hydrogen produced will contain less energy than the materials and agents used to produce it; the energy efficiency in the manufacture of hydrogen will be less than 1. Hydrogen can be manufactured from natural gas with an energy efficiency of about 70%. Hydrogen can be produced by the electrolysis of water with an efficiency of about 70%, but this does not include the efficiency of the production of electricity, which itself is not a fuel and must be produced from a fuel such as natural gas, oil, coal, or uranium. The energy efficiency of generation of electricity is about 35%.

An important consequence

A consequence of this relationship of hydrogen to fuel is that hydrogen will always cost more than the cost of the fuel plus the cost of the energy used to make it. Since manufactured hydrogen will always contain less energy than the fuel and the “other energy” used in its formation, *direct* use of the fuel and “other energy” will always be more efficient than any indirect use of these resources.

How big is hydrogen?

Elemental hydrogen exists as a gas at room temperature and atmospheric pressure. Under these Standard conditions of Temperature and Pressure, STP, the volume of hydrogen gas that contains the same amount of energy as one gallon of gasoline is about 3,200 gallons. That’s right: it takes thirty two hundred gallons of hydrogen gas, STP, to provide an amount of energy equivalent to that of a gallon of gasoline. For hydrogen to be a practical form of chemical energy, therefore, hydrogen must be made smaller.

Making hydrogen smaller

There are two ways to make hydrogen smaller. The first is to squeeze it, and the second is shrink it. That it, hydrogen must be stored either as a compressed gas at normal temperatures or as a liquid at 20 Kelvin. Both compression and liquefaction can reduce the “gallon-of-gas-equivalent” volume of hydrogen to about 3.6 gallons, but no less. The “gallon-of-gas-equivalent” volume of hydrogen cannot be made any smaller than about 3.6 gallons.

Energy efficiency in the storage of hydrogen

We now consider the energy efficiency of these two ways to store hydrogen. However, before we consider the energy efficiency of squeezing or shrinking hydrogen, we will consider first the energy efficiency of “pumped storage” of water because squeezing a gas is like pumping water uphill.

Efficiency of pumped storage of water

In pumped storage of water the excess electrical energy produced by hydroelectric generation during times of low demand is used to pump water up to a reservoir at a higher altitude. Later, during periods of high demand, when the normal generating capacity is insufficient, additional power can generated by allowing the water in the higher reservoir to flow back down through additional generators.

A representative energy efficiency for the overall round trip for the water, from the lower reservoir, through the pump up to the higher reservoir, and then back down through the generator to the lower reservoir again, is about 80%. Thus about 1.25 units of electrical energy must be used to produce 1 unit of electrical energy by way of “pumped storage”. We can represent the process in this way.

electrical energy	$\xrightarrow{\text{pumped storage}}$	electrical energy
before pumped storage		**after pumped storage**
1.25 units of energy	**80% efficiency**	**1 unit of energy**

As you can see, more energy is used in pumping than is regained in later use; the efficiency of the process is less than 1.

Why would one want to “waste” electrical energy in this way? The answer is: so as to better match the ability to generate electrical energy to the demand for electrical energy. It is a way to store excess electrical energy until it is needed. Apparently the benefit is worth the energy “cost”.

We now consider the energy efficiency of squeezing or shrinking hydrogen.

Efficiency of compression of hydrogen

Just as a liquid such as water can be pumped to a state of higher energy, so can a gas be pumped, or squeezed, or compressed, to a state of higher energy. There is also, as with the pumping of water, an energetic cost.

When a gas is compressed it can get hot; remember how your bicycle pump gets hot when you blow up the tires on your bicycle. The degree of heating, however, depends upon how rapidly the gas is compressed.

If the compression is done very slowly, most of the heat of compression will be passed to the surroundings, the pump, or compressor, and the temperature of the gas itself will rise only a little. If, on the other hand, the compression is done very rapidly the compressed gas will at first be hot. The compressed gas will later cool to the temperature of the surroundings.

Slow compression requires less energy than rapid compression. With slow compression the resisting pressure of the gas goes up only because the volume of the gas is made less. With fast compression, however, the resisting pressure of the gas goes up not only because the volume of the gas is made less but additionally because the gas get hotter. Since the energy required to compress a gas is proportional to the resisting pressure it will take more energy to compress a given amount of gas if the temperature of the gas rises during compression. The “extra” energy that is needed for rapid compression is ultimately transferred to the surroundings as thermal energy, as the hot compressed gas cools, and the extra energy is thereby lost.

Once again we see that there is an “energy tax” applied when we want to do something quickly, whether it be pumping electrons, pumping water, or pumping a gas.

For rapid compression to 200 atmospheres (200 bar), the extra energy required is equivalent to 10% of the chemical energy of the hydrogen gas. For “multistage” compression, a compromise between fast compression and slow compression, the energy cost is equivalent to about 8% of the chemical energy of the hydrogen gas.

When losses to friction and the inefficiency of the electric motors used to run the compressors are included in the reckoning, the energy cost of compression of hydrogen to 200 atmospheres comes to about 20% of the energy content of the hydrogen subjected to compression.

Why compress hydrogen?

Why would anyone “waste” energy in this way? The answer is: To make hydrogen smaller so that it can be more cheaply and easily stored and transported.

We can represent the energy efficiency of the compression of hydrogen to 200 atmospheres (200 bar) in this way.

total energy	$\xrightarrow{\text{compression to 200 bar}}$	*hydrogen* energy
before compression		**after compression**
1.2 units of energy	**83% efficiency**	**1 unit of energy**

Efficiency of liquefaction of hydrogen

A second way of making hydrogen gas smaller is to shrink it by cooling. When hydrogen gas is cooled to –253 °C. or 20 Kelvin the molecules finally touch, stick together, and fall to the bottom of the container; the gas becomes a liquid. It will, however, remain a liquid only if its temperature is kept below the boiling point of the liquid, 20 K, or –253 °C. This is a very low tempera-ture, and it is not easy to cool anything to this degree.

For very small liquefaction plants, plants that produce about 25 gallons of liquid hydrogen per hour, the energy required to liquefy the hydrogen is as great as the energy of the liquefied hydrogen; the energy efficiency of liquefaction of hydrogen on this scale is only 50%.

total energy	$\xrightarrow{\text{liquefaction}}$	*hydrogen* energy
before liquefaction		**after liquefaction**
2 units of energy	**50% efficiency**	**1 unit of energy**

We can estimate that a liquefaction plant 100 times bigger, 2,500 gallons of liquid hydrogen per hour, could have a somewhat higher efficiency, perhaps as high as 70%. Such a plant has not yet been built.

total energy	$\xrightarrow{\text{liquefaction}}$	*hydrogen* energy
before liquefaction		**after liquefaction**
1.4 units of energy	**70% efficiency**	**1 unit of energy**

Liquid hydrogen and the space shuttle

You might wonder why liquid hydrogen is the fuel of choice for the space shuttle. The reason is that 3.6 gallons of liquid hydrogen *weighs* only 2.1 pounds, only 1/3 as much as the weight of a gallon of gasoline, its energy equivalent, or a gallon of jet fuel. Thus when weight is most important and volume is secondary, as with the space shuttle, hydrogen can be the fuel of choice.

The external tank of the space shuttle holds 400,324 gallons of liquid hydrogen. At 2,500 gallons per hour this liquefaction plant, which has not yet been built, would take 160 hours (almost one week, operating 24/7) for it to produce that much liquid hydrogen. The shuttle burns it in 8.45 minutes.

One of the reasons for the low energy efficiency of the liquefaction of hydrogen is the ortho to para conversion. At room temperature 75% of the hydrogen gas is present as the higher energy ortho form, and 25% is present as the lower energy para form.

At the temperature of liquid hydrogen, however, 99.8% of the liquid hydrogen is present as the more stable para form.

$$\text{ortho hydrogen} \rightleftharpoons \text{para hydrogen} + \text{energy}$$

75%	**300 K**	**25%**
0.02%	**20 K**	**99.8%**

The ortho to para conversion takes place as the temperature is lowered during liquefaction, and the thermal energy that is released as this conversion takes place must also be removed during the liquefying process.

The ortho to para conversion is actually quite slow, but it is encouraged to take place during liquefaction. If this is not done, and the ortho to para conversion is allowed to take place after liquefaction, the energy released by the conversion is sufficient to revaporize 30% of the liquefied hydrogen. This would be an unacceptable loss of liquid hydrogen.

Boil off of liquid hydrogen

Another “cost” of liquefaction of hydrogen is loss of material during storage. While hydrogen under pressure can be stored without loss, this is not true of liquid hydrogen. Some of the stored material will evaporate each day during storage. The size of the loss of hydrogen by “boil-off” is exactly the same each day, whether the tank is almost full or almost empty, because the rate of evaporation equals the rate at which heat enters the tank.

Sometimes the loss by boil-off is accepted, but in larger installations the escaping vapor is collected and reliquefied. In either case, “boil off” is another cost of liquefying hydrogen. It is an energy cost because both replacement and reliquefaction use energy.

Why liquefy hydrogen

Why would anyone “waste” energy by liquefying hydrogen? Again, the answer is: to make it and its container smaller and lighter. Ten times more hydrogen can be transported as a liquid in a cryogenic hydrogen tanker as can be transported as a gas at 200 bar in a tube trailer.

Energy efficiency in the transport of hydrogen

Hydrogen can be transported as a gas at “ordinary” conditions of temperature and pressure, or as a compressed gas at, say, 200 atmospheres, or as a liquid at 20 Kelvin.

None of these methods is acceptable for long-distance transport. Hydrogen, like electricity, must be produced close to where it is needed.

Transport as a gas at “ordinary” conditions

Hydrogen at “ordinary” conditions of temperature and pressure can be transported short distances by pipeline. Hydrogen that is now transported in this way is a chemical commodity, not a fuel, and the cost of transport is only a small part of the cost of the final product that contains the hydrogen. The cost of transport is then easily passed on to the consumer.

Comparison to pipeline transport of natural gas

Since the volumetric energy density of hydrogen is less than one third that of methane under the same conditions, the velocity of hydrogen through a pipeline of the same diameter would have to be more than three times the velocity of methane to give the same flow of energy.

For a pipeline 2000 miles long the energy efficiency for the transportation of methane would be about 80%, but for hydrogen it would be only 67%. We can represent the comparison in this way.

total energy	$\xrightarrow{\text{2000 mile pipeline}}$	*gas* energy
before transportation		**after transportation**
1.25 units of energy	**80% efficiency**	**1 unit of methane energy**
1.50 units of energy	**67% efficiency**	**1 unit of hydrogen energy**

For gas pipelines the required energy is taken from the transported gas as needed. If this were done for hydrogen pipelines, however, only 2/3 of the hydrogen would survive the 2,000 mile trip, and this would be unacceptable.

The hydrogen, even if made from natural gas, would be too valuable to use in this way. The energy would have to come from some other source.

Transport of hydrogen as a compressed gas

As we mentioned before, hydrogen can be transported at a pressure of 200 bars (about 200 atmospheres), in tube trailers. However, because of the weight of the tubes, a 80,000 pound gross weight tube trailer can carry only 1,000 pounds of hydrogen, and can deliver only 800 pounds. It returns with 200 pounds of hydrogen undelivered, at a weight on the return trip of 79,200 pounds.

The reason the tube trailer cannot be emptied is that the hydrogen is typically delivered into a 40 bar tank, and thus the pressure at delivery can be reduced only to 42 bar. The tube trailer can deliver only 158/200, or about 80% of its load. If the tube trailer is to be emptied, or is to deliver into a, say, 700 bar storage tank, the hydrogen must be pumped from the tubes.

Transport of hydrogen as a cryogenic liquid

Cryogenic hydrogen can be delivered in special cryogenic tankers of 60,000 pounds gross weight that deliver about 4,000 pounds of hydrogen to the customer. Thus one hydrogen delivery by a cryogenic tanker has about 5 times the energy content of one hydrogen delivery by a tube tanker.

Comparison with other fuels.

Instead of calculating delivery costs for tube tankers and cryogenic tankers we will compare payloads. The assumptions are that all 80,000 pound gross weight trucks will have comparable operating costs, and that those with the higher total Higher Heating Value (HHV) payloads will be the more energy efficient for delivery of energy.

The following table presents some comparative data.

	H_2 gas	**H_2 liquid**	**ethanol**	**propane**	**gasoline**
gross weight	80,000	60,000*	80,000	80,000	80,000
delivery weight	800	4,000	52,000	40,000	52,000
relative HHV	0.045	0.238	0.616	0.805	1.000

gross weight: pounds; delivery weight: pounds, higher heating value: relative to gasoline.

*Cryogenic hydrogen tankers are limited to 30 tons gross weight.

The rules of energy

Nature follows rules. We can watch what Nature does, and we can “test” Nature by trying something to see what happens. If we pay attention and think hard we can often figure out what the rules of Nature must be.

The rules of energy tell us how energy works. The rules of energy are among the most general and useful rules of Nature.

The first rule of energy

The first rule of energy is that energy always comes from somewhere. Energy does not come from nothing. Since electricity does not occur in nature in a useful form we must convert a naturally occurring form of energy into electrical energy. Similarly, since elemental hydrogen does not occur in useful amounts here on Earth, we must produce elemental hydrogen from a naturally occurring source of combined hydrogen.

In neither case will the new material, electricity or hydrogen, have more energy than the materials and energy consumed in its production.

Where did the energy come from?

The short answer is “from the sun”. The energy of “fossil fuels”, coal, oil, and natural gas, are products of “ancient” sunlight, while the energy of the wind, waves, falling water, and “biomass” are products of “recent” sunlight.

We can then ask Where does the sun’ s energy come from? and gradually work our way back to ask Where did everything come from? At this time we will go back only as far as the energy of the sun.

The second rule of energy

The first rule of energy is that all new energy must come from old energy. The second rule of energy is that the new energy will be *smaller* in amount than the old energy that is used to make the new energy. The reason that the “new” energy will be smaller in amount than the “old” energy needed to make the “new” energy is that, *inevitably*, some heat will be produced during the formation of the “new” energy.

The second rule, like the first rule, is a statement of *experience*. There have been no exceptions. No amount of research or wishful thinking will change this. It is a fact of nature, just as universal gravitation is a fact of nature. The electrical energy produced will always be less than the energy required to make it. The energy of hydrogen produced will always be less than the energy required to make it. The efficiency of any change in the form of energy will always be less than 1, because, inevitably, some heat will be given off.

What if you want to make heat?

If your goal is the production of heat, or thermal energy, the efficiency of its formation can be 1. It *is* possible to *completely* turn other forms of energy into thermal energy. But it is not possible to completely turn thermal energy into any other form of energy.

Why is thermal energy different?

Thermal energy, or heat, is the outward manifestation of random and disordered atomic and molecular motion. It is this insight that allows us to understand the existence of an “absolute zero” of temperature. The “absolute zero” of temperature is the temperature at which all heat has been removed. Absolute zero is the temperature at which all thermal energy is gone. Absolute zero is the temperature at which all random and disordered atomic and molecular motion has ceased.

Coherent motion

Other motions, such as the flow of water, the flow of electrons, the motion of the wind and the tides, the swing of a pendulum, are *coherent* motions; the parts move together. Ordered, or coherent, motion is much less likely than random or disordered motion. Once the random state has been attained, it is impossible to go back. There are far more ways to be random than there are ways to be ordered. It is entirely a matter of probability. Random states are inevitable. Coherent energy ultimately becomes thermal energy. Ordered energy ultimately becomes disordered energy.

The efficiency of energy conversion must be less than 1

We can now understand why new energy will be *smaller* in amount than the old energy that is used to make the new energy. During the conversion some of the “old” energy becomes heat, and not all the heat can become “new” energy. This limit was discovered after the first “steam” engines were built.

Efficiency of heat engines

Early “steam” engines, the most familiar examples of heat engines, were quite inefficient. It might take 10 units of coal energy to produce one unit of mechanical energy, or “work”. Nine units of energy had merely become heat. We can summarize the situation in this in this way *coal* energy $\xrightarrow{\text{steam engine}}$ *"work"* energy

10 units of coal energy	**10% efficiency**	**1 unit of "work" energy**

Quite naturally, the question was asked: how efficiently can "heat" energy be turned into "work" energy or other forms of "useful" energy. The answer is: the efficiency of a heat engine will always be less than 1 unless the temperature of the environment is 0 K!

How efficient can we get?

It is sometimes possible to be very efficient by moving very slowly. If you move so slowly that, by very, very slightly reducing the "push" you will move in reverse your efficiency will be at its maximum. Move any faster than this and resistive forces, or friction, appear, and heat is produced. Once heat is produced, and all "real" processes produce heat, the energy efficiency of the process will be less than 1.

Efficiency of real processes

While an "ideal" process might have an efficiency of almost 1, "real" processes will be less efficient. "Frictionless" bearings do not exist, nor do frictionless pistons, turbines, or wires exist, superconductors excepted.

We saw earlier in the electrolysis of water that an "electron pressure", or voltage, much greater than the minimum possible was needed in order to attain an acceptable rate of electrolysis. Similarly in the compression of a gas a much greater pressure than the minimum possible pressure is needed in order to attain an acceptable rate of compression. At the higher rates the losses to friction are greater, and the efficiencies are correspondingly smaller.

Overall energy efficiency

So far, we have considered the efficiency of a single process. Examples have included production of hydrogen by steam reforming of natural gas (0.70, or 70% energy efficiency), and the compression of hydrogen gas to 200 bar (0.83, or 83% energy efficiency).

A two-step process

What if we wanted to know the overall energy efficiency of production of hydrogen gas by steam reforming followed by compression of the gas to 200 bar? The overall efficiency would be the product of the efficiencies of the two steps, in this case the product of 0.70 and 0.83, which is 0.58. The two steps together have a combined energy efficiency of 0.58, or 58%.

$$\text{fossil fuel} \xrightarrow[\text{reforming}]{\text{steam}} \quad \xrightarrow[\text{to 200 bar}]{\text{compression}} \text{hydrogen at 200 bar}$$

1 times 0.70 times 0.83 equals 0.58

It’s like cutting a pie. If the first person leaves you half a pie (0.50), and the next person leaves you half of what’s left (0.50), you will have left only 0.50 times 0.50, or 0.25 of a pie.

Another way to look at this pie example is to ask how many pies you should start with so that after the first person takes half of them, and the second person takes half the remainder you will have exactly one pie. In this case you can see that you had better start with four pies. The math is 1/0.25 = 4.

Applying this math to the hydrogen example we can see that in order to have one unit of energy in the form of hydrogen at 200 bar at the end of the two steps you would need to start the steam reforming process with 1/0.58 = 1.72 units of energy. To check, we see that 1.72 times 0.70 times 0.85 = 1.

$$\text{fossil fuel} \xrightarrow[\text{reforming}]{\text{steam}} \quad \xrightarrow[\text{to 200 bar}]{\text{compression}} \text{hydrogen at 200 bar}$$

1.72 times 0.70 times 0.83 equals 1

More examples of overall energy efficiency

We can calculate other overall efficiencies in the same way.

Fossil fuel to electricity to hydrogen gas STP to hydrogen gas at 200 bar

Suppose we want to estimate the overall energy efficiency of going from a fossil fuel to electricity (efficiency of electrical generation = 0.35) to hydrogen gas at STP (efficiency of electrolysis = 0.70) to hydrogen gas compressed to 200 bar (efficiency of compression = 0.83). We would multiply the three efficiencies, 0.35 x 0.70 x 0.83, to get = 0.20, or an overall efficiency of 20%.

Thus, to get 1 unit of hydrogen energy at 200 bar we would need to start with 5 times that much energy in the form of fossil fuel.

Fossil fuel to electricity to hydrogen gas STP to liquid hydrogen at 20K

Suppose, instead of compressing the hydrogen, as in the example just above, we consider liquefying the hydrogen (efficiency of liquefaction = 0.70). The overall efficiency, starting with fossil fuel, would then be 0.35 x 0.70 x 0.70 =

0.17, or 17%. We would then need to start with 1/0.17 = 5.9 units of energy in the form of fossil fuel to get 1 unit of energy in the form of liquid hydrogen.

Back to The Dream

Let's now review the dream....

Production, transport, and storage

> "The Central Mission of the United States Department of Energy Hydrogen Program is to research, develop, and validate fuel cell and hydrogen production, [transport], and storage technologies."

We have seen that the production, transport and storage of hydrogen will consume large amounts of other forms of energy. The main reason for this is that *hydrogen is not a fuel*; rather, a fuel must be consumed so as to make it.

Furthermore, the production of hydrogen necessarily consumes more energy than is contained in the hydrogen that is produced. Steam reforming of methane consumes 1.4 times the energy of the hydrogen that is produced. *Steam reforming of coal* consumes 2.3 times the energy of the hydrogen that is produced. And consumes 1.4 times the energy of the hydrogen that is produced.

Finally, the necessary compression or liquefaction of hydrogen will consume additional energy, energy that must also be provided by a fuel. *Compression* will consume additional energy in an amount equivalent to about 20% of the energy of the compressed hydrogen. *Liquefaction* will consume additional energy in an amount equivalent to at least 40% of the energy of the liquefied hydrogen.

Overall, as we have just seen, about 5 units of fuel energy will be required to provide 1 unit of hydrogen energy, either as a compressed gas or as a cryogenic liquid.

Diverse, domestic, clean, safe, reliable, affordable

> "Hydrogen from diverse domestic resources will then be used in a clean, safe, reliable, and affordable manner in fuel cell vehicles and stationary power applications."

Hydrogen must be made from a fuel, and therefore hydrogen will be no more domestic, clean, safe, reliable, or affordable than the fuel used to make it. Imported oil is not domestic. Imported gas is not domestic. Electricity made from imported oil or gas is not domestic. While coal will necessarily be domestic, electricity made from coal will be no cleaner than the coal used to make it. And, finally, since more energy will be consumed than will be contained by the hydrogen that is produced, the hydrogen will necessarily be more expensive than the fuel used to make it.

Abundant, reliable, affordable, and clean

> "Development of hydrogen energy will ensure that the United States has an abundant, reliable, and affordable supply of clean energy to maintain the Nation's prosperity throughout the 21st century."

Again, since the production of hydrogen consumes fuel, hydrogen will be no more abundant, reliable, affordable, or clean than the fuel used to make it.

Hydrogen: the realities

Any plan for a "hydrogen economy" must take into account the following characteristics of elemental hydrogen.

1. Elemental hydrogen does not occur in Nature; hydrogen is not a fuel.

2. Production of hydrogen will consume existing fuels.

3. Hydrogen can be made from natural gas or petroleum, but only until natural gas and petroleum are used up.

4. Hydrogen can be made from water and coal.

5. Hydrogen can be made from water and coal, but only until the coal is gone.

6. Hydrogen can be made from water by electrolysis. The production of hydrogen by electrolysis will be limited by the amount of electrical energy available for this purpose. The amount of electrical energy required will be 1.4 times the energy content of the amount of hydrogen that is required.

7. There is no compensating "convenience" factor that favors conversion of another form of energy to hydrogen energy. There is, instead, an "inconvenience" factor: the low density of hydrogen. The fact that the STP volume of hydrogen gas that contains the same amount of energy as one gallon of gasoline is about 3,200 gallons requires that hydrogen gas be either compressed or liquefied before transport or storage. Compression to 200 bar will require energy in the amount of 20% of the energy of the hydrogen to be compressed. Liquefaction will require energy in the

amount of 40% of the energy of the hydrogen to be liquefied.

Formation of carbon dioxide

In addition to taking into account the characteristics of elemental hydrogen, any plan for a hydrogen economy must also take into account the formation of carbon dioxide in the production of hydrogen.

Here are the facts:

1. In the production of hydrogen from natural gas or petroleum *all* the carbon of the fossil fuel is converted to carbon dioxide.
2. In the production of hydrogen from water and coal *all* the carbon of the coal is converted to carbon dioxide.
3. Production of hydrogen from water and coal produces twice as much carbon dioxide as production of hydrogen from methane.
4. The electrolysis of water is no more free of the production of carbon dioxide than is the process used to make the electricity.

The choices

We can use the energy of fossil fuels directly, as we do now, or we can use their energy indirectly by using them to make hydrogen, and then to either compress or liquefy the hydrogen. The energy efficiencies of these overall processes are no better than 20%, which means that to make one unit of energy in the form of hydrogen will require 5 units of fossil fuel energy.

Choosing hydrogen also implies construction of factories for the manufacture, compression, and liquefaction of hydrogen, along with facilities for its storage, transport, and delivery to the consumer.