March 11, 2003

A Cost-Saving Optimization to the Hydrogen Economy

By

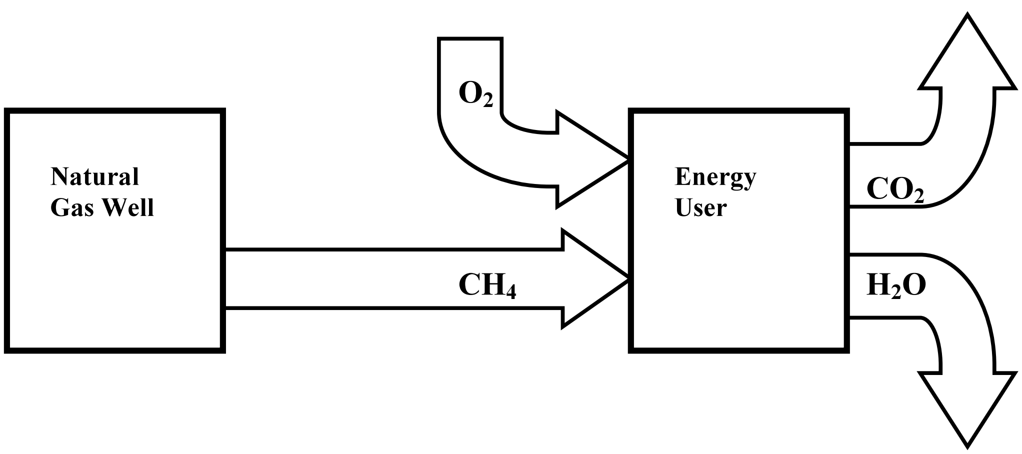
James H. Beyer

The 'Hydrogen Economy' has been proposed to eliminate carbon dioxide (CO_2) emissions, believed to threaten the world with global warming, and at the same time, make renewable energy resources (such as solar and wind power) easier to use by our energy economy.

While maintaining this basic premise, an optimization can be applied to the proposed Hydrogen Economy, allowing it to work more efficiently. CO_2 is used as a hydrogen carrier, chemically bonding to hydrogen at the source of energy production. This bonding can result in a number of possible fuels, including methane and methanol. The fuel is then combusted or reformed at the point of energy use normally, with the exception that the CO_2 produced is retained, and sent back to the energy source. A two-pipe transport (one pipe transporting a hydrocarbon such as methane (CH_4) to the energy user, and another pipe transporting CO_2 back to the energy source) replaces the single pipe of hydrogen to the energy user. Because of the greatly increased energy density of a hydrocarbon fuel, this energy transport scheme is cheaper than moving hydrogen, even accounting for the overhead of moving CO_2 back to the energy source.

Since hydrogen bound to carbon dioxide produces fuels we already use, this optimization is much less imposing on our current infrastructure than using a totally new fuel such as hydrogen. Interim strategies can send CO_2 from existing sources with retention capabilities (such as coal-fired electrical production or ethanol production facilities) while more widespread CO_2 retention technology is developed. Energy from renewable sources will be accessible and stable in price and quantity. CO_2 will also be valued or 'monetized', facilitating CO_2 emission reduction.

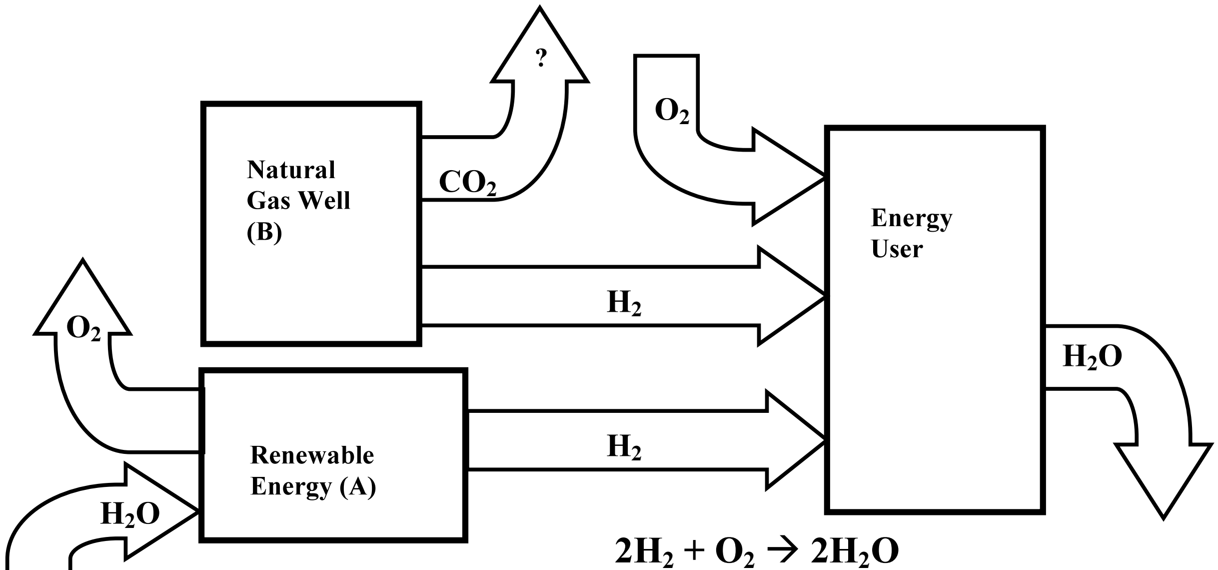
In order to explain this optimization in greater detail, first consider how our energy use with fossil fuels occurs now:



$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Fossil fuels (represented by methane, CH_4) provide energy but at the expense of us producing CO_2 emissions. Renewables (solar and wind producing grid electricity) have some utility, but they are a weak source of intermittent energy, and cannot contribute easily to our energy needs. This is because electricity cannot be economically stored, and the intermittent nature of the energy cannot be easily incorporated in an infrastructure that needs and relies upon steady and predictable sources of power.

To address the role of renewables, and to avoid CO_2 emissions, we have considered what is called the Hydrogen Economy:



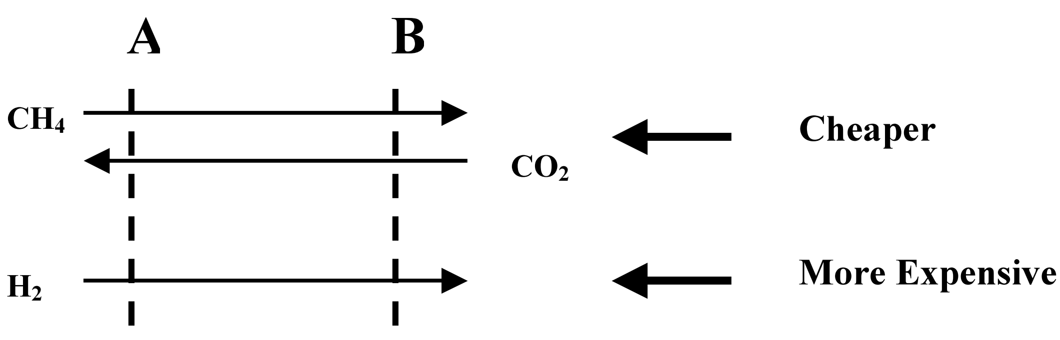
$$2H_2 + O_2 \rightarrow 2H_2O$$

In this setting, renewables (A) use their electrical power output to produce hydrogen by the electrolysis of water. The hydrogen is then piped to energy users (industry), which use it instead of hydrocarbons for power. Since its combustion product is only water, no carbon dioxide is produced. In the interim, to make up for the energy needs of our country, fossil fuels (B) can produce hydrogen by separating carbon dioxide from a hydrocarbon fuel source with a reformation process. The CO_2 byproduct must be sequestered or is simply vented. If renewable energy is not employed, the hydrogen economy does not avoid CO_2 emissions; it just hides them.

While this setting works in theory, there are some concerns with it. First, our entire infrastructure has to change to make use of hydrogen. Second, hydrogen itself, while energetic, is bulky and difficult to store or to transport. Renewable energy is only accessible after this hydrogen infrastructure is in place.

Hydrogen is so difficult to move, consider this assertion:

Between any two points A and B, it is cheaper to transport methane from A to B and a like (molar) quantity of carbon dioxide from B to A, than it is to simply transport hydrogen (of equal energy content) from A to B.



If you wish to grasp this notion practically, consider that the two major methods of moving hydrogen are either through a pipeline or some kind of storage tank (which is itself moved):

In the case of the storage tank, it is well known that compressed methane is a denser energy carrier than hydrogen. A given tank at a given pressure will hold more energy in methane than it would hold in hydrogen. After discharging, the hydrogen tank must be returned empty to the source for refueling. The methane tank is instead filled with carbon dioxide on its return trip. The carbon dioxide has a "free ride" with the returned container.

In the case of the pipeline, methane is more than twice as dense (energetically) than a given volume of hydrogen at the same pressure. So two pipelines, one containing methane, and one containing carbon dioxide (moving in the opposite direction), can carry more energy than a single pipeline that is more than twice the size, containing only hydrogen at the same pressure.

This assertion can be more formally supported by considering the following. Hydrogen has an energy capacity of 33.90 kilowatt-hours/kilogram. Methane has a capacity of 13.44 kilowatt-hours/kilogram. Since a mole of hydrogen is 2 grams, there are 500 moles of hydrogen per kilogram. Since a mole of methane is 16 grams, there are only 62.5 moles of methane per kilogram. So, on a mole basis, the energy content of hydrogen is 0.0678 kilowatt-hours/per mole. Methane, however, has a capacity of 0.215 kilowatt-hours per mole. Since the combustion of one mole of methane produces one mole of carbon dioxide, the 'overhead' of the zero energy carbon dioxide is another 62.5 moles per kilogram (of methane). Even accounting for this 'overhead', the energy capacity of methane/carbon dioxide is still 0.1075 kilowatt-hours/mole. This is more than 58% greater than hydrogen.

Why is the energy content per mole so important? Because the work required to compress a gas is dependent on the number of moles of the gas, not its weight:

$$W = m \bullet R \bullet T \bullet \ln(V_{init}/V_{final})$$

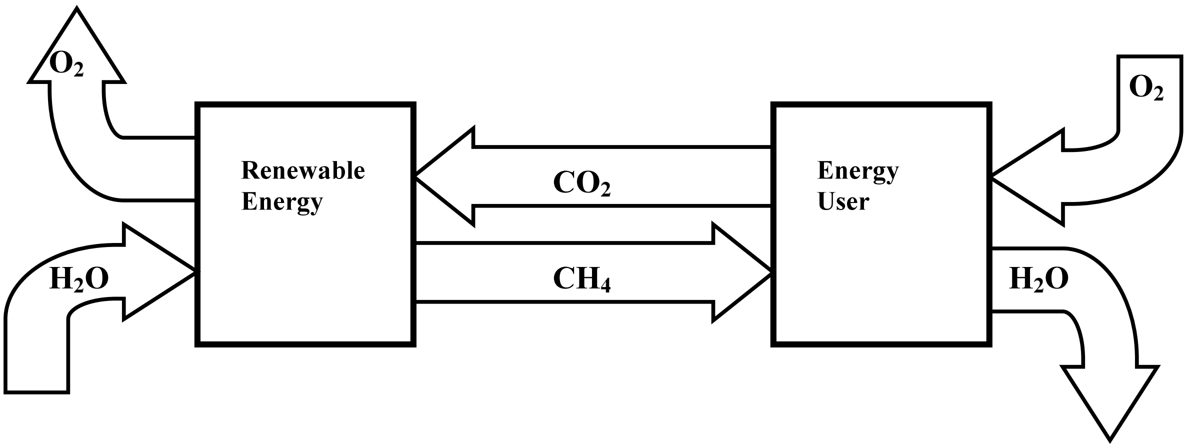
Where:

W is the work performed
m is the number of moles of gas
R is the gas constant
T is the temperature in Kelvin
V_{init} is the initial gas volume
V_{final} is the final gas volume

Since methane is more than twice as dense energetically than hydrogen, even the combined compression costs of both the methane and carbon dioxide gases are less than hydrogen singly.

If other hydrocarbons are substituted for methane (such as methanol (CH_3OH) or ethane (C_2H_6) or propane (C_3H_8), then the advantages over hydrogen are even more pronounced.

Since it is cheaper, consider using the hydrogen economy plan, but instead replacing a single pipe of hydrogen with two pipes, one of methane going from energy production to energy use, and the other carbon dioxide going from energy user to energy production. What happens? Well, the system looks a bit more like our current economy:

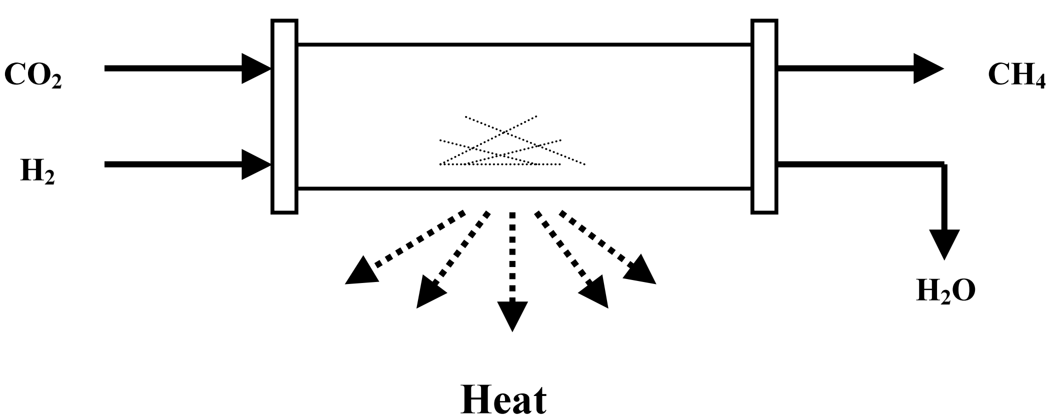


(1) $4H_2O \rightarrow 4H_2 + 2O_2$
(2) $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ **$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$**
Net: $CO_2 + 2H_2O \rightarrow CH_4 + 2O_2$

On the energy user side, the concept is understandable. Instead of venting CO_2, it is sent back on the return tube. This should be fairly easy to do. For large users of energy, retaining CO_2 is done regularly. Retaining CO_2 is not the problem; it is what to do with it once you have it. Overall, energy users will be happy to have a place to send their CO_2.

On the production side, the situation is more confusing. What is an energy producer going to do with CO_2? Since they are supposed to provide CH_4, how are they going to get that? In turns out, there is a device that can do this. It is called a Sabatier reactor (Paul Sabatier, 1854-1941), and was used in the 19th Century gaslight era to produce natural gas from hydrogen. A Sabatier reactor is simply a metal tube containing a nickel catalyst. (Ruthenium is another catalyst.) They are simple, reliable devices:

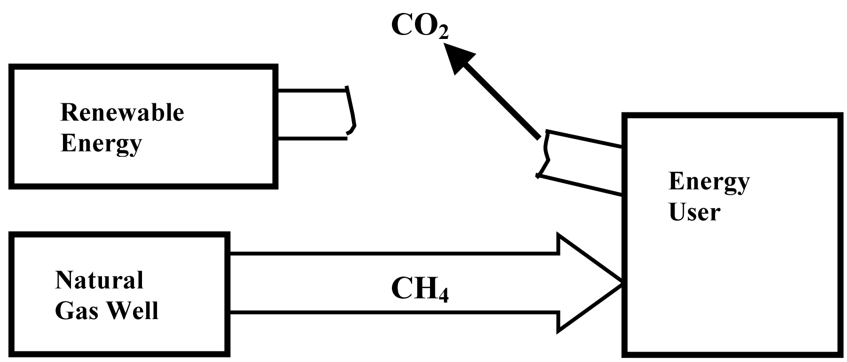
Sabatier Reactor



$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ ΔH +40 kcal/mole

About 79% of the energy content of hydrogen remains in the methane. The rest becomes heat. Since this reaction occurs at the production site, some of this heat can be recouped by heating a steam boiler or other apparatus. Overall a renewable energy site may be 70-90% efficient in producing methane (using CO_2 as an input) versus 90-95% efficient in producing hydrogen alone. Both concepts vent oxygen to the atmosphere, but the pure hydrogen production requires nearly twice as much water for the same amount of energy stored. The methane produced is carbon neutral.

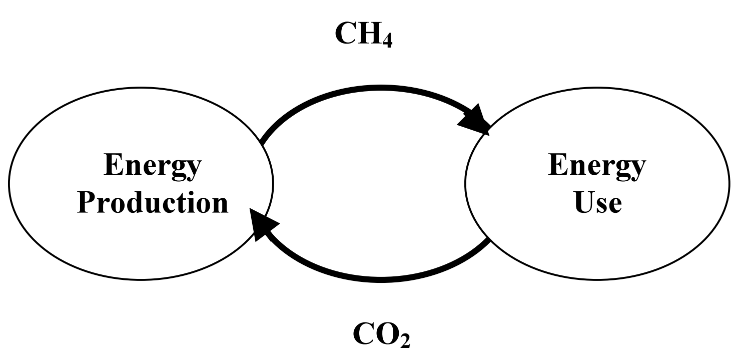
Look what this provides for us. Low quality, intermittent, dispersed renewables provide us with methane! This can be readily used by our energy economy, by piping CO_2 to our renewables, which many energy users would like to get rid of anyway! We can turn our wind farms into gas wells, simply by sending them CO_2 that had been destined for sequestering (storing CO_2 instead of allowing it to go into our atmosphere). Carbon emissions would be saved by not using the natural gas resource that would otherwise have been tapped. In retrospect, let's review our current energy system:



We can see in this context, that it is clear that our current system could be seen to be "broken". There is a "pipe" that is needed to send CO_2 to our renewable energy sources. The energy users are venting carbon dioxide, and our renewable energy sources are starved of carbon dioxide, and can't produce viable energy. But if we just fix the break in the "pipe", then not only is the problem fixed, but we are de facto functioning as the hydrogen economy. This is clearly what we must do.

For a further clarification consider the analogy of plants and animals. The animal eats and breathes, consuming oxygen, and hydrocarbons and producing carbon dioxide. The plant consumes carbon dioxide, producing oxygen and hydrocarbons. The cycle is stable, and uses the atmosphere to transfer carbon dioxide from animal to plant.

Our technology needs to match this:



Unlike plants, we cannot easily pick carbon dioxide out of the atmosphere. It is much easier for us to supply a pipe. In the same way our technological energy use is a "mechanical animal" consuming and breathing, our renewable power production must be "mechanical vegetation" fixing hydrogen to carbon dioxide. As long as we keep these in balance, we will not threaten the environment with global warming by our technology.

To put it another way, carbon dioxide is the "hydrogen carrier" that we have been looking for to make the hydrogen economy work. It is used simply by combusting it, and it is restored in the Sabatier reactor. Like any carrier, the empty holder (carbon dioxide) needs to be shuttled back to the energy source for re use.

Like an electrical power, we need to "plug-in" our methane. And like electrical power, we need a return line to send the spent methane (carbon dioxide) back to the energy source.

Methane is also much easier to store in bulk than hydrogen would be. Again, this is true even accounting for the overhead of also storing carbon dioxide in bulk. For renewable energy to be practically accessible, this bulk storage is needed to moderate the fluctuations of energy use with the varying rates of renewable energy production (including seasonal variation).

In the case of motor vehicles, they do not need to run on hydrogen. Instead, they can run on compressed or liquefied natural gas. All that is needed is that the carbon dioxide be retained during use. This can be done by using multiple tanks, several filled with methane, and one empty. The CO_2 is returned to the empty tank, and then, as a tank with fuel is exhausted, it too becomes available to hold CO_2. Refueling is done by evacuating the CO_2 and refilling it with methane. The CO_2 is sent back on the return line to the renewable energy source. No fuel cells, no liquefied hydrogen, no problematic range problems, and no emissions. The CO_2 emitted from a typical natural gas vehicle can also be replaced, or 'swapped' with CO_2 created as a byproduct of fuel production from biomass.

Alternatively, if one wishes to employ fuel cells, methane can be reformed on site at the refueling facility, the CO_2 returned to the source of energy production. The hydrogen can then be used by the vehicle, releasing only water vapor.

We can solve our carbon emission problems and at the same time, end our dependency on fossil fuels. This can be done with a minor impact on our current infrastructure, and the resulting energy will be stable, domestically produced, and low cost.

Jim Beyer V2.3

Pat. Pend.

Jim Beyer
Vision Instruments
P. O. Box 7143
Ann Arbor, MI 48107-7143
USA

jimjhb@aol.com