WORKSHEETS FOR COMPUTING THE LEVELIZED COST (US$/gasoline gal equivalent; Euro/gasoline L equivalent) AND CARBON CONTENT (lb-CO_2/gasoline gas equivalent; kg-CO_2/gasoline L equivalent) OF HYDROGEN VEHICLE FUEL PRODUCED AT A MODEL WIND ELECTRIC POWERED HYDROGEN ELECTROLYZER

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ABSTRACT

This paper is a response to Kreith and Isler's August, 2002 Journal of Solar Energy Engineering Discussion Note, *Comments Dealing with Fuel Cell Energy Policy and Renewable Energy.* This paper first discusses the technical and economic principles underlying the levelized cost method of computing the cost (US$/gal-HVF; Euro/L-HVF) and carbon content (lb-CO_2/gal-HVF; kg-CO_2/L-H_2) of a gallon of hydrogen vehicle fuel (HVF) produced by a wind (grid) electric powered hydrogen electrolyzer (HE). Topics include global warming and greenhouse gas (GHG) emissions, the conventional methods of producing industrial hydrogen (H_2), HE technology, CO_2 emissions from internal combustion engine vehicles (ICEV) and fuel cell vehicles (FCV), CO_2 emissions from H_2 production, gasoline gallon equivalent (GGE) of a gal-HVF, HE capacity (MW, gal-H_2/yr; L-H_2/yr;), HE efficiency-%, HE capacity cost-US$/MW; Euro/MW, physical life of a HE-yr, HE availability-%, HE capacity-%, electric energy (wind, grid) cost (US$/MWh; Euro/MWh), gal-HVF/yr (L-HVF/yr) produced, levelized cost method, depreciation, capital cost-%, cost of capital, fixed and variable non-electric energy operating and maintenance (O&M) costs and taxes. The paper then compares the carbon emissions (lb-CO_2/100mi; kg-CO_2/100km) of the current US passenger ICEV Fleet with a proposed US passenger FCV fleet

The paper includes two worksheets, "Levelized Cost (US$/gal-$H_2$; Euro/L-$H_2$) and Carbon Content (lbs-CO_2/gal-H_2; kg-CO_2/L-H_2) of HVF Produced at a Model Wind Electric Powered 1 MW HE with Benchmark Values for a Model Plant Located in Iowa next to a Model 1 MW Wind Plant" and "A Comparison of the Carbon Emissions (lb-CO_2/100mi; kg-CO_2/100km) and Fuel Costs (US$/100mi; Euro/100km) of the Current US Passenger ICEV Fleet with a Proposed US Passenger FCV Fleet". There is also a list of nomenclature.

This paper was presented at the American Solar Energy Society (ASES) Solar 2003 Conference, June 21-25, 2003, Austin, TX. I presented another version of this paper with Euro and SI units (kg, km, L) at the 2003 European Wind Energy Conference, 16-20 June 2003, Madrid, Spain. On October 18, 2003 I presented this paper to the 33rd Annual Illinois Economics Association Meeting.

This paper has now been submitted to the *Journal of Solar Energy Engineering* (JSEE). I would like to get some more professional and academic feedback during the December 19th NCAC-USAEE Monthly Luncheon. Reader comments are welcome. Benchmark values have not been updated since June 21.

1. THE REASON THAT THIS PAPER WAS WRITTEN

Atmospheric GHG (such as NO_X, CO and CO_2) absorb infrared energy from the earth's surface and prevents it from leaving the earth. This paper focuses on carbon dioxide (CO_2) emissions, the major GHG. The human activity of driving a gasoline fueled ICEV fleet has increased the atmospheric concentration of CO_2 to such a high level that the earth's surface temperature is rising. This global warming will cause catastrophic changes to our planet's climate. A H_2 fueled FCV fleet has been proposed as a replacement for the current US ICEV fleet because a FCV, by itself, does not emit any CO_2 (i.e. lb-CO_2/100mi; kg-CO_2/100km) as it operates. From a GHG environmental perspective, if there were no global warming, there would be no need to discuss a US FCV fleet. We could continue to drive the current US ICEV fleet.

This paper has been written in response to the August, 2002 Journal of Solar Energy Engineering Discussion Note, *Comments Dealing with Fuel Cell Energy Policy and Renewable Energy* [1]. Kreith and Isler's major comment was that "…because of the efficiency of producing hydrogen with current available technologies from natural gas, the use of hydrogen fuel cells in automobiles will actually increase the generation of greenhouse gases unless the hydrogen was produced by electrolysis using electric power generated from non-polluting sources such as solar thermal or wind". These authors' position was it was becoming "…more important to place serious R&D effort on reducing the cost of producing hydrogen vehicle fuel from solar sources that produce less greenhouse gases than fossil fuels".

There were three points in Kreith and Isler's Discussion Note. Kreith and Isler's first point was that a FCV operates without emitting carbon, but except for a wind powered HE, the conventional production of HVF emits carbon. Their second point was that any carbon emitted in the production of HVF must be attributed to the FCV fleet. Their third point was that because of this attribution, the proposed FCV fleet must be powered with carbon free HVF or the carbon emissions attributed to the FCV fleet will be greater than the carbon emissions from the current ICEV fleet.

The first part of this paper is based on my August, 2002 JSEE Technical Brief, *A Financial Worksheet for Computing The Cost (¢/kWh) of Solar Electricity Generated at a Grid Connected Photovoltaic (PV) Generating Plant* [2].

This paper discusses the monetary and physical values in US$ and US English standard units [3] (lb, mi and gal) although the Euro and SI units (kg, km, L) are also used. This is done so that the price of HVF can be compared to the price of gasoline which, in the US, is priced in US$/gal (Euro/L). It is also done so that the fuel efficiency of the proposed FCV fleet can be compared with the fuel efficiency of the current ICEV fleet which, in the US, is measured in mpg (L/100km). mpg (L/100km) is the measurement for the energy efficiency of a vehicle.

Worksheets #1 and # 2 are presented with the US$ and English values converted into Euro and SI units. The paper uses US$1.1870/Euro [4] which is the highest US$/Euro rate since the Euro was introduced on 4 January 1999. Readers are cautioned not to assume that the purchasing power parity hypothesis of classical Anglo-American economic theory predicts monetary values in the wholesale electric and gasoline markets of countries that use the Euro as their monetary unit. Readers can replace the Euro with another monetary unit.

Terms specific to this paper are abbreviated after their first use in the paper. A list of these terms and their abbreviations is at the end of this paper. Certain other abbreviations used in this paper are also listed.

2. H_2 PRODUCTION, GAL-HVF AND CO_2 EMISSIONS

H_2 does not occur in commercial amounts in nature and must be produced.

H_2, produced as an industrial gas, is measured by volume: standard cubic foot (SCF) (SI; nominal cubic meter [Nm^3]). Alternatively H_2 can be measured by mass: lb (kg) or by energy content: mmBtu (MWh, GJ). H_2, produced as an industrial gas, is priced in US$/SCF (Euro/$Nm^3$). H_2, produced as HVF, should be measured and priced in the unit of measure, gasoline gallon equivalent, gal-HVF, (SI; L-HVF-gasoline liter equivalent). The gasoline gallon equivalent unit, gal-HVF (L-HVF), will, hereafter, be referred to as gal-H_2 [L-H_2].

Gal-H_2 (L-H_2) is a unit of energy, not a unit of volume. The energy content (exact conversion ratio) of gasoline is 0.036362 MWh/gal, (0.0096838 MWh/L) (0.13091 GJ/gal) (0.12407 mmBtu/gal) [5]. The inverse of the conversion ratio is 27.50124 gal-H_2/MWh (103.26464 L-H_2/MWh). The paper does not take into consideration the high HHV (39.30 kWh/kg) and low LHV (33.20 kWh/kg) heat values of H_2 [6]. Using the LHV as the base, the maximum difference is 18.4%.

Current [7] US industrial H_2 production technologies (i.e. reformation of natural gas (NG) [48%], oil [30%], coal gasification [18%]) use hydrocarbons as a feed stock and emit CO_2 as a by-product of the H_2 production. In a literature search, the author was unable to find benchmark GHG emission values (U/K lb-CO_2/SCF, U/K kg-CO_2/Nm^3, U/K lb-CO_2/gal-H_2, U/K kg-CO_2/L-H_2) for any of the industrialized hydrocarbon based H_2 production technologies. The author hopes that this paper will encourage readers to ask industry, US government and academic researchers to publish benchmark HVF CO_2 emission values for each industrialized hydrocarbon based H_2 production technology.

A FCV that runs on gal-H_2 produced at a wind powered HE runs carbon emission free. A FCV that uses H_2 fuel produced from NG or other hydrocarbon feed stocks does not run carbon emission free when the CO_2 emissions from the HVF production from the HVF production are included in the computation of the FCV emissions. CO_2 emissions from HVF produced with fossil fuels should be measured in lb-CO_2/gal-H_2 (kg-CO_2/L); CO_2 emissions from the proposed FCV fleet should be measured in lbs.-CO_2/100mi (kg-CO_2/100km)

Electric energy is applied to water (H_2O) to separate it into gaseous H_2 and oxygen (O_2). A HE is an electrolytic cell designed to control the dissociation of water into H_2 and O_2 [$2H_20 \Rightarrow 2H_2+O_2$] using as little electric energy (i.e. maximum efficiency) as is possible. The dissociation reaction is controlled with catalysts. With electric energy, H_2O is catalytically decomposed into protons, electrons and O_2 gas at one electrode (anode) of the electrolytic cell. The protons move through the electrolyte to the other electrode (cathode) of the electrolytic cell. At the same time, electric power is applied to the electrons and they are forced to flow through an external circuit to the cathode. The catalytically controlled reaction of protons and electrons at the cathode produces H_2 gas. There are different types (i.e. alkaline, proton exchange membrane [PEM]) of HE because of the different catalysts, electrolytes and cell structures used. A discussion of the different types of HE is beyond the scope of this paper.

A HE uses electricity to produce H_2 and O_2. A FC uses H_2 and O_2 to generate electricity. Because HE and FC are mirror image technologies, readers may want to refer to the author's paper, A *Financial Worksheet for Computing the Cost (US$/MWh) of Electricity Generated at a Grid Connected Hydrogen Fuel Cell Electric Generating Plant* [8].

3. THE ORGANIZATION OF THE FIRST WORKSHEET

Worksheet #1 is at the end of the paper.

In Section 3, the paper will go over the first worksheet's Wind Column with 2002 benchmark variable values for a model 1 MW HE located in Iowa next to a model 1 MW wind plant. In Section 4, the paper will go over the first worksheet's Grid Column with 2002 benchmark values.

Entering different variable values on the worksheets causes the worksheets' computed values to change.

The worksheets do not adjust any monetary values for inflation.

HE capacity can be measured in terms of input or output. HE efficiency links the input and output values. HE production capacity has traditionally been measured in electric power input, MW_{input} (hereafter, MW), and priced in US$/MW. The wind (or grid) electricity to power the HE is measured in MWh_{input} (hereafter, MWh) and is priced in US$/MWh. HE HVF production capacity is measured in units of output, gal-H_2/yr_{output} (hereafter gal-H_2/yr; L-H_2/yr).

HE efficiency is the percent of the energy in 1 MWh of wind electricity that is converted into gal-H_2. A 100% efficient HE will produce 27.50124 gal-H_2/MWh (exact conversion ratio) from 1 MWh of wind electricity. An 80% efficient HE will produce 22.00099 gal-H_2/MWh. A 50% efficient HE will produce 13.75062 gal-H_2/MWh.

The model 1 MW HE has a maximum capacity of 8,760 MWh/yr (1 MW X 8,760 hr/yr [24/365]). A 100% efficient 1 MW HE has a capacity of 240,911 gal-H_2/yr (8,760 MWh/yr X 27.50124 gal-H_2/MWh). An 80% efficient model 1MW HE has a capacity of 192,729 gal-H_2/yr. A 50% efficient 1 MW HE has a 124,456 gal-H_2/yr capacity.

Worksheet #1, Wind Column, Line 2, HE Capital Cost-US$/MW, the variable benchmark value is US$1,000,000/MW (US$1,000/kW). This value is the author's estimate. The author did not find actual published manufacturers' prices for the HE Capital Cost. A 1 MW commercial HE is a much more mature technology than a FC. US$4,500,000/$MW_{output}$ (US$4,500/kWh) is one [9] published FC capacity cost; Mann, DiPietro, Iannucci and Eyer [10] assumed US$600,000/$MW_{input}$ for a HE (US$600/kW for 2000; US$300kW for 2010).

A HE has a physical life (years). During its physical life, as the HE produces H_2, both the initial capital cost (MW x US$/MW) of the HE must be recovered (depreciation) and the cost of capital (interest) for using the invested capital must be paid.

If borrowed money is used to buy the HE plant, the cost of borrowing the money is called the lender's interest. If the plant owner uses their own money to buy the plant, the cost of using the owner's money is called the owner's

return on investment (ROI). The cost of capital interest rate (%) is a weighted average percent for both the lender's interest and the owner's ROI.
The levelized cost method [2] uses a financial annuity to compute one constant yearly payment (capital amortization cost) for both the depreciation of the power plant and the interest over the physical life of the plant. This level (constant) capital amortization expense gives the method its name. The first year's payment is almost all interest, while the last year's payment is almost all depreciation.

In order for a cost computation method to accurately compute the cost of a gal-H_2, the rate of physical deterioration of the HE should determine the rate of financial depreciation. It is in the later years of a its life that a HE incurs most of its loss in H_2 production capacity. The levelized cost method assigns most of the deprecation to the later years of the HE's life.

For this paper, "back of the envelope" simplicity is one criteria for a computation method. A second criteria is an accurate first approximation of the cost US$/gal-$H_2$ (Euro/L-H_2) to produce HVF at a HE. The levelized cost method meets both criteria.

Wind Column, Line 9, Physical Life of HE-years, the benchmark variable value is 25 years. Wind plants are expected to last 20-25 years. 25 years is a reasonable benchmark.

Line 10, Interest Rate/ROI-%, the benchmark value is 10%. 10% is, from the author's experience, in the "ballpark" for American power plants.

Line 11, Capital Amortization Factor-CAF, is computed to be 0.11017. The CAF is the annual payment computed for an annuity having US$1.00 as the principal amount borrowed, a loan period of 25 years (Line 9) and an interest rate of 10% (Line 10).

Line 4, Constant MWh/gal-H_2,the constant value [5] is 0.036362 (36.36 kWh/gal-H_2),. This value is the exact conversion ratio. The inverse is 27.50124 gal-H_2/MWh (103.26464 L-H_2/MWh).

Line 13, HE Efficiency-%, the benchmark value is 80%. Mann, DiPiertro [10], etc., assumed an 80% HE efficiency for 2000 and 87% for 2010. Thomas and Kuhn [11] assumed 67.5% LHV and 80% HHV.

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Line 5, Electric Energy (wind, grid) Cost-US$/MWh, the benchmark value is US$40/MWh (4.0¢/kWh) [33.70Euro/MWh; 3.37 Euro/kWh]. A Wednesday, March 26, 2003 IRR Industry Alert article [12] reported that the current average US wholesale delivered price for wind electricity to be US$45/MWh (4.5¢/kWh). There is no transmission charge in this example because the model HE is located in Iowa right next to the model 1 MW wind plant. US$5/MWh (4.21 Euro/MWh) is the author's estimate of the avoided transmission charge.

HE efficiency determines the MWh that a HE plant uses to generate 1 gal-H_2. A 100% efficient HE would use Line 4, 0.036362 MWh, to generate 1 gal-H_2. With a US$40/MWh wind electric cost, a 100% efficient HE would have the Wind Column, Line 20, Electricity Cost-US$/gal-$H_2$, computed value US$1.45 This is US$40 x 0.036362. An 80% efficient HE would have an Electricity Cost of US$1.82 (US$40 x 0.04545). 0.04545 is 0.036362 divided by 0.80. A 50% efficiency HE would have an Electricity Cost of US$2.91 (US$40 x 0.07272).

Computing the gal-H_2/yr that the model 1 MW HE plant will produce is required to compute Line 20, Total Levelized Cost-US$/gal-$H_2$. HE availability is the percent of hours per year that the HE is available to operate. No maintenance or down time would mean 100% availability (24/365) or 8,760 hr/yr. The more hr/yr that the HE is available, the more gal-H_2/yr that the HE can produce.

This worksheet assumes 100% HE availability. King and O'Day [13] reported 40,000 hours as the 5 year overhaul period for a FC, a less mature technology than a 1 MW commercial HE. 40,000 hours is 91.3% of the actual 43,800 hours in five years (8,760 X 5). 100% availability is a good value for simplifying Worksheet #1.

The HE capacity factor is the percent of hours per year that the model 1 MW HE is operating at full input capacity (that is, at full power of 1 MW/hr). If the model HE has a 100% availability, and if it operates 8,760 hr/yr, it has a 100% capacity factor and uses 8,760 MWh/yr.

Line 12, HE Capacity Factor-%, the benchmark value is 35%. 35% means that the HE operates at full power 3,066 hr out of 8,760 hr per year (3,066/8,760=35%). The larger the capacity factor-%, the more gal-H_2/yr the HE can produce.

The model 1 MW HE operates on wind electricity. The 1 MW HE is directly powered by a 1 MW wind plant. A wind electric plant, like a HE plant, has a capacity factor. The wind plant capacity determines the HE capacity. Wind is an intermittent source of electricity. Mann, DiPietro [10], etc., assumed a 35% wind plant capacity factor for 2000 (40% for 2010).

Wind Column, Line 14, H_2 Produced per Year-gal-H_2/yr, the computed value is 67,455. This is the product of 27.50124 gal-H_2/MWh, X 8,760 X Line 12, 35%, X Line 13, 80%. If Wind Column, Line 12, Capacity Factor, were 70%, Line 14, would be 134,910 gal-H_2/yr.

There are many mechanical (tanks, pumps, fans, valves, etc.) and electronic (printed wiring boards, switches, etc.) parts in a HE. The HE stack has to be over hauled ever 5 years. This means that a HE has fixed (scheduled) and variable (operating) O & M Costs.

Line 7, Annual Fixed O & M Cost-Percent of HE Capital Cost, Line 2, the benchmark value is 3%. King and O' Day [13] expect 5 years between FC overhauls. MW commercial HE have better reliability than current FC. Mann, DiPietro [10], etc., assumed 3% of capital cost for all (fixed and variable) 2000 operating costs (2% for 2010). The author believes that the 3% benchmark value is reasonable.

Line 8, Non-Electric Energy Variable O & M Cost-US$/gal-$H_2$, the benchmark value is US$0.15/gal-$H_2$. The author believes that this benchmark value is reasonable.

The worksheet does not include taxes. Taxes are an additional expense and would add to the cost of the H_2 produced by the model HE. Real estate taxes add to the fixed O & M Cost. Income taxes require that the before tax ROI be higher because income taxes reduce the after tax ROI.

Line 15, Annual Amortization Cost-US$/yr, is computed to be US$110,168. This is US$1,000,000 (Line 2) X 0.11017 (Line 11).

Line 16, Annual Fixed O & M Cost-US$/yr, is computed to be US$30,000. This is 3% (Line 7) X
Line 2.

Line 17, Levelized Annual Cost-US$/gal-$H_2$, is computed to be US$2.07795. US$2.07795 is the sum of US$110,168 (Line 15) plus US$30,000 (Line 16) divided by US$67,455 (Line 14). The more gal-H_2/yr produced, the smaller Line 17.

On Line 18, Levelized Annual Cost- US$/gal-$H_2$, Line 17 is rounded and transferred as US$2.08/gal-$H_2$ (US$2.07795→US$2.08).

Line 19, Variable O & M Cost-US$/gal-$H_2$, is US$0.15/gal-H_2 which is transferred from Line 8 above.

Line 20, Electricity Cost--US$/gal-$H_2$, is computed to be US$1.82. First, Line 4, 0.036362, is multiplied by Line 5, US$40. Then this product is divided by Line 13, 80%. The higher the HE efficiency, the lower Line 20.

Wind Column, Line 21, Total Levelized Cost-US$/gal-$H_2$, is computed to be US$4.05. US$4.05 is the sum of Line 18, US$2.08, plus Line 19, US$0.15, plus Line 20, US$1.82. Line 18, is 51% of Line 21; Line 19, is 4% and Line 20, 45%.

Line 1, Gasoline Spot Price-US$/gal, the benchmark value is US$0.82/gal (0.18 Euro/L). The Monday, March 24, 2003 Wall Street Journal reported that the Friday, March 21 spot price for unleaded premium non-oxygenated gasoline was US$0.8175/gal [14]. The gasoline spot price is the wholesale price without taxes and distribution expenses. The gasoline spot price is a good benchmark value with which to compare the production cost of a gal-H_2.

Line 23, Total Level Cost (above) below Spot Price-US$/gal, is computed to be (US$3.23). The worksheet subtracts Line 21, US$4.05, from Line 22, US$0.82. A negative value means that the production cost of a gal-H_2 is more expensive than the spot price of gasoline.

4. USING GRID ELECTRICITY TO INCREASE THE HE CAPACITY FACTOR

Section 4 uses Worksheet #1's Grid Column as well as its Wind Column. The reader should note which column values Section 4 is referring to.

Grid Column, Line 12, HE Capacity Factor-%, the benchmark value is 100%. The gird is always on. 100% is 65% more than the Wind Column, Line 12, benchmark value, 35%. The HE is now powered by grid electricity when the wind electricity is not available (65% of the time). Allowing the HE to be powered by grid electricity when wind electricity is not available also requires that the Grid Column, Line 6, Wind Electricity-%, benchmark value be 35% instead of the Wind Column, Line 6 value, 100%.

If Grid Column, Line 12, is 100% and Grid Column, Line 6 is 35% and if all the other Grid Column benchmark values are kept the same as the Wind Column values, the increase in the capacity factor increases the HE production of HVF. Grid Column, Line 14 is computed value to be 192,729. 192,729 is 185.7% more gal-H_2/yr than 67,455.

The increased gal-H_2/yr computed on the Grid Column, Line 14 (compared to Wind Column, Line 14) reduces the Grid Column, Line 17 and 18 computed values. Grid Column, Line 18, Levelized Annual Cost-US$/gal-$H_2$, is reduced 65% from US$2.08 to US$0.73. This is because the annual amortization and fixed O & M costs are spread over a larger number of gal-H_2/yr.

Grid Column, Line 21, Total Levelized Cost-US$/gal-$H_2$, is computed to be US$2.70. US$2.70 is a reduction of 33.4% from Wind Column, Line 21, US$4.05.

Line 18 is the only component of Grid Column, Line 21 to change values. The % of each component on Grid Column, Line 21 does change. Grid Column, Line 18 is computed to be US$0.73 (27% of Grid Column, Line 21; US$2.08 is 51% of Wind Column, Line 21). Grid Column, Line 19, remains at US$0.15 (6% of Grid Column, Line 21; US$0.15 is 4% of Wind Column, Line 21). Grid Column, Line 20, remains at US$1.82 (67% of Grid Column, Line 21; US$1.82 is 45% of Wind Column, Line 21).

69% [15] of 1999 US grid electricity was generated with fossil fuels. Using grid electricity means powering the HE with fossil fuel electricity.

Line 3, Yearly Average CO_2 Emissions-lb-CO_2/MWh US Generation Mix, the benchmark value is 1,351 lb-CO_2/MWh (1.351 lb-CO_2/kWh) for 1999. This 1999 value is from an Wind Energy Association spreadsheet [15].

Wind Column, Line 24, CO_2 Emissions-lb-CO_2/gal-H_2, is computed to be 0.0 lb-CO_2/gal-H_2. Grid Column, Line 24 is computed to be 40.2 lb-CO_2/gal-H_2. Using grid electricity to increase the HE Capacity Factor increases the carbon content of a gal-H_2 from 0.0 to 40.2 lb-CO_2/gal-H_2 (4.8 kg-CO_2/L-H_2).

In both Worksheet #1 Columns, Line 24 first computes the % of Grid electricity that the HE uses. The computation is 100% minus Line 6. Wind Column, Line 24, the % of Grid electricity computed is 0.0%. This is 100% minus Wind Column, Line 6, 100%. Grid Column, Line 24, the % of Grid electricity computed is 65%. This is 100% minus Grid Column, Line 6, 35%.

In both Worksheet #1 Columns, Line 24 then equals the product; % of grid electricity X Line 3 (lb-CO_2/kWh) X Line 4 (kWh/gal-H_2). This product is then divided by Line 13, HE Efficiency-%.

Wind Column, Line 24 the computed value is 0.0% because the product of 0.0% and any other multiplicands is always zero. A 100% wind electric powered HE produce HVF with 0.0 lb-CO_2/gal-H_2. The Grid Column, Line 24 computed value is 40.2. 40.2 is the product of 65% X 1,351 (Line 3) X 0.036362 (Line 4) divided by 80% (Line 13).

When the HE produces HVF with 100% wind electricity, the HVF has zero carbon content.

5. A QUANTITATIVE DEMONSTRATION OF KREITH AND ISLER'S THREE POINTS

Variable and computed values from the Worksheet #1 Wind and Grid Columns are used by the second worksheet in a quantitative demonstration of Kreith and Isler's three points.

The second worksheet is also at the end of the paper.

Worksheet #2 has two columns. The ICEV Column is for the current US Passenger ICEV Fleet. The FCV Column is for a proposed US Passenger FCV Fleet.

On the second worksheet, the FCV Column is referred to with [brackets].

The vehicle fuel price, US$/gal-gasoline (Euro/L-gasoline) [US$/gal-$H_2$ (Euro/L-H_2)], and ICEV [FCV] fleet fuel efficiency, mi/gal (L/100km), determine the ICE [FCV] fleet fuel cost to drive, US$/100mi (Euro/100km). The fuel price and the fleet fuel efficiency are the independent variables. The fleet fuel cost to drive is the dependent variable. Nevertheless, if one has values for any two of the three variables, the third variable can be determined.

The carbon content of the vehicle fuel, lb-CO_2/gal-gasoline (kg-CO_2/L-gasoline) [lb-CO_2/gal-H_2 (kg-CO_2/L-H_2)], and the ICEV [FCV] fleet fuel efficiency, mi/gal (L/100km), determine the fleet carbon emissions, lb-CO_2/100mi (kg-CO_2/100km). The fuel's carbon content and the fleet fuel efficiency are the two independent variables. The fleet carbon emissions is the dependent variable. If one has values for any two of the three variables, the third variable can be determined.

The engineering economics goal (as contrasted with the political economic goal) is a US passenger auto fleet with the least carbon emissions at the least fuel cost. The proposed FCV fleet is a means to reach this goal. The engineering economics must take Kreith and Isler's three points into consideration.

FCV Column, Line A, HE CO_2 Emissions-lb-CO_2/gal-H_2, the benchmark value is 40.2. Line A does not use the ICEV column. 40.2 is the computed value on Worksheet #1, Grid Column, Line 24.

Worksheet #2 demonstrates Kreith and Isler's first point that a FCV operates without emitting carbon, but except for a wind powered HE, the conventional industrial production of HVF emits carbon. 0.0, the computed value on Worksheet #1, Wind Column, Line 24, is not used. By entering 0.0, the reader could follow how the second worksheet attributes zero CO_2 emissions to the FCV fleet, when the HVF is produced at a HE that only uses wind electricity.

Worksheet #2 demonstrates Kreith and Isler's second point that the CO_2 emissions from the HVF must be attributed to the FCV fleet. By entering 40.2, the reader can follow how the second worksheet attributes to the FCV fleet, CO_2 emissions (lb-CO_2/100mi), when the HVF is produced at a grid connected HE that uses electricity that has a carbon content (or whenever HVF is produced with hydrocarbon feed stocks).

ICEV Column, Line B, Fuel Cost-ICEV US$/gal-gasoline, the benchmark value is US$0.82. This is the same benchmark value that was entered on Worksheet # 1, Line 1.

FCV Column, Line B, [FCV US$/gal-$H_2$], the benchmark value is US$2.70. US$2.70 is the computed value on Worksheet #1, Grid Column, Line 24. US$2.70 is 229% (3.3 times) greater than US$0.82.

ICEV column, Line C, ICEV Fleet Average-mi/gal, the benchmark value is 21.5. 21.5 is the value reported by the US EPA on its web page, *Emission Facts* [16], for the US ICEV Passenger Vehicle Fleet. The EPA web site did not specify the calendar, model or fiscal year for this mi/gal value.

FCV Column, Line C, [FCV Fleet- mi/gal], the variable benchmark value is also 21.5. For now, the paper assumes that the proposed US FCV Fleet is as fuel efficient as the ICEV fleet. Both fleets have the same mpg.

ICEV Column, Line D, US ICEV Passenger Vehicle Fleet Average CO_2 Emission-lb-CO_2/mi, the benchmark value is 0.9160 lb/mi. 0.9160 is the July, 2000 value for the ICEV fleet as reported by US EPA [16]. Line D does not use the FCV column.

FCV Column, Line E, Proposed FCV-Fleet-Emissions-lb-CO_2/mi, is computed to be 1.8698. 1.8698 is 40.2 (Line A) divided by 21.5 (Line C). Line E does not use the ICEV column.

ICEV Column, Line F, Compare ICEV verse [FCV], CO_2 Emissions, lb-CO_2/100mi, the ICEV Column computed value is 91.6; the FCV Column value is 187.0. 91.6 is the value 0.9160 is transferred from ICEV Column, Line D above and multiplied by 100 mi. 187.0 is 1.8698 transferred from FCV Column, Line E above and multiplied by 100 mi. 187 is 104% greater CO_2 emissions (twice) than 91.6.

Worksheet # 2 demonstrates Kreith and Isler's third point that when the CO_2 emissions from the HVF are attributed to the FCV fleet, the carbon emissions attributed to the proposed FCV fleet will be greater than the carbon emissions from the current ICEV fleet. The computation on ICEV Column, Line F shows that with CO_2 emissions of 40.2 lb-CO_2/gal-H_2 [FCV Column, Line A) and with the FCV fleet's fuel efficiency set at 21.5 mi/gal (FCV Columns, Line C), the proposed FCV fleet is computed to emit twice the carbon that the current ICEV Fleet does.

If FCV Column, Line C, variable value is set at 43.9 mi/gal-H_2 (104% fuel efficiency increase over 21.5 {twice the mpg}), the FCV and ICEV fleets would have the same carbon emissions, 91.6 lb-CO_2/mi (ICEV & FCV Columns, Line F).

ICEV Column, Line G, CO_2 Emissions-lb-CO_2/gal-gasoline, is computed to be 19.7. 19.7 is 21.5 (ICEV Column, Line C) X 0.9160 (ICEV Column, Line D). Line G does not use the FCV column.

21.5 mi/gal is an independent variable; 0.9160 lb-CO_2/mi is the dependent variable. Both variables are used to compute the second independent variable, Line G, the carbon content of gasoline. 19.7 lb-CO_2/gal-gasoline must be the computed value if the published independent and dependent variable values just cited are accurate. Readers can use their own public references to see if this check number is accurate. Reader comments on these values are welcome.

ICEV & FCV Columns, Line H, Comparison: ICEV lb-CO_2/gal-gasoline verse [FCV lb-CO_2/gal-H_2], the value 19.7 is transferred from ICEV Column, Line G above; the value 40.2 is transferred from FCV column, Line A above. The FCV's 40.2 lb-CO_2/gal-H_2 is 104% greater (2 times) than the ICEV's 19.7 lb-CO_2/gal-gasoline.

Worksheet #2, Line H, also demonstrates Kreith and Isler's second and third points by showing that HVF produced at grid powered HE has more carbon content (4.8 kg-CO_2/L-H_2) than current GFV (2.4 kg-CO_2/L-gasoline).

Worksheet #2, Line H is physically correct. If there is 100% efficiency in converting a fossil fuel such as gasoline (lb-CO_2/gal-gasoline) into grid electricity and if the HE has 100% efficiency in converting the grid electricity into HVF, the HVF would have the same carbon content (lb-CO_2/gal-H_2) as the fossil fuel, gasoline. If there is less than a 100% efficiency, the HVF will have a higher carbon content than the fossil fuel used to generate the grid electricity.

If the reader does not agree that the Worksheet #2 benchmark values are accurate, the reader can enter their own variable values on the worksheet.

ICEV Column, Line I, ICEV Fleet [FCV Fleet] Fuel Cost to Drive-US$/100mi, the computed value is US$3.81 (US$3.81 of gasoline is used to drive 100 miles). US$3.81 (2.00 Euro/100km) is US$ 0.82 (ICEV column, Line B) divided by 21.5 (ICEV Column, Line C) times 100. FCV column, Line I, the computed value is US$12.56. (US$12.56 of H_2 is used to drive 100 miles). US$12.56 (6.57 Euro/km) is US$2.70 (FCV column, Line B) divided by 21.5 (FCV Column, Line C) times 100. The fuel cost for the FCV fleet is 229% more than (3.3 times) the ICEV fleet.

6. SENSITIVITY ANALYSIS FOR THE FIRST WORKSHEET

Section 4 contains sensitivity analysis for Worksheet #1. The following cases are presented as additional sensitivity analysis for Worksheet #1.

a) If Wind Column Line 12, Capacity Factor Cost, is increased 35% to 70% (100% increase), and if all the other benchmark values are kept the same, Line 14, H_2 Produced a Year-gal-H_2, will increase from 67,455 to 134,910 (100% increase) and Line 21, Total Levelized Cost, is reduced 25.7% from US$4.05 to US$3.01/gal-H_2 (0.90 Euro to 0.67 Euro/L-H_2).

b) If Wind Column Line 1, Capital Cost, is reduced 50% from US$1,000,000 (842,460 Euro) to US$500,000 (421,230 Euro), and if all the other benchmark values are kept the same, Line 21, Total Levelized Cost, is also reduced 25.7% from US$4.05 to US$3.01/gal-H_2.

c) If after Line 1 above, is reduced to US$500,000, Wind column, Line 13, HE Efficiency, is increase from 80% to 87% (8.8% increase). If all the other benchmark values are kept the same, Line 21, is reduced 31.4%, from US$4.05 to US$2.78/gal-H_2 (0.62 Euro/L-H_2).

d) If after Line 13 above is increased to 87% , while Line 1, remains at US$500,000, Line 12, HE Capacity, is increased from 35% to 40% (14% increase). If all the other benchmark values are kept the same, Line 21, is reduced 34.3%, from US$4.05 to US$2.66/gal-H_2.

e) The March 26, 2003 IRR Industry Alert article also reported the average wholesale US delivered price [12] for grid electricity from "more established generating sources" to be US$30/MWh. If Grid Column, Line 5, Electricity Cost, is decreased 25% from US$40 to US$30/MWh, and if all the other benchmark values are kept the same, Line 21, Total Levelized Cost, is reduced 16.9% from US$2.70 to US$2.24/gal-H_2.

Readers can do their own sensitivity analysis by entering their own variable values on the first worksheet.

7. SENSITIVITY ANALYSIS FOR THE SECOND WORKSHEET

The following cases are presented:

a) If the FCV Column, Line C, average mi/gal-H_2, is increased from 21.5 mpg to 35 mpg (63%) and if all the other ICEV and FCV Column benchmark values are kept the same, FCV Column, Line F FCV Emissions lb-CO_2/100mi, is reduced 39% from 187 to 114.9. 114.9 is still 25% greater than ICEV Column, Line F, 91.6 lb-CO_2/100mi.

b) If the FCV Column, Line A, Emissions lb-CO_2/gal-H_2, is reduced 50% from 40.2 to 20.1 lb-CO_2/gal-H_2 and if all the other ICEV and FCV Column benchmark values are kept at the same, FCV Column, Line F, FCV Emissions lb-CO_2/100mi, is reduced 50% from 187 to 93.5 lb-CO_2/100mi. 93.5 is only 2% greater than ICEV Column, Line F, 91.6 lb-CO_2/100mi.

c) If after Line A above is reduced to 20.1 lb -CO_2/gal-H_2, FCV Column, Line B, FCV US$/gal-$H_2$, is reduced 33.3% from 2.70 to US$1.80/gal-$H_2$, and if all the other benchmark values are kept the same, FCV Column, Line I, Fuel Cost to drive 100 mi, is reduced 33.3% from US$12.56 to 8.37.

Readers can do their own sensitivity analysis by entering their own variable values on the second worksheet.

8. CONCLUSIONS

These conclusions are valid for both the USA and the rest of the planet. Converting the US$ and English values into Euro and SI units does not change the economic or physical facts.

A FCV passenger fleet has been proposed to replace the current US ICEV passenger fleet. Kreith and Isler's first point was that a FCV operates without emitting carbon, but except for a wind powered HE, the conventional production of HVF emits carbon. Their second point was that any carbon emitted in the production of HVF must be attributed to the FCV fleet. Their third point was that because of this attribution, the proposed FCV fleet must be powered with carbon free HVF or the carbon emissions attributed to the FCV fleet will be greater than the carbon emissions from the ICEV fleet. Based on the facts (variable values used) and computational methods presented (worksheets # 1 and # 2), Kreith and Isler's three points have been demonstrated in this paper.

This paper's specific conclusions are:

1. Current industrial H_2 production technologies that use hydrocarbon feed stocks to produce HVF will produce gal-H_2 (L-H_2) with a carbon content (U/K lb-CO_2/gal-H_2; U/K kg-CO_2/L-H_2) greater than GVF (19.7 lb-CO_2/gal-gasoline; 2.4 kg-CO_2/L-gasoline).
2. Readers are encouraged to ask industry, US government and academic researchers to publish yearly benchmark HVF carbon content values for each industrialized hydrocarbon based H_2 production technology. These values can then be entered on this paper's Worksheet # 2, Line A.
3. Using wind electricity to power a HE will produce HVF with no carbon content (0.0 lb-CO_2/gal-H_2; 0.0 kg-CO_2/L-H_2) and a FCV fleet with no CO_2 emissions from operations (0.0 lb-CO_2/100mi; 0.0 kg-CO_2/100km). The current price (US$4.05/gal-$H_2$; 0.90 Euro/L-$H_2$) of this wind H_2 is much too expensive to use to power a FCV passenger vehicle fleet.
4. Using grid electricity to power a HE will produce HVF with a carbon content (40.2 lb-CO_2/gal-H_2; 4.8 kg-CO_2/L-H_2) greater than the current GVF (19.7 lb-CO_2/gal-H_2; 2.4 kg-CO_2/L-H_2) and a FCV fleet with CO_2 emissions from operations greater than the current ICEV fleet. The current price (US$2.70/gal-$H_2$; 0.60 Euro/L-$H_2$) of this gird H_2 is also too expensive to use as a fuel to power a FCV fleet.
5. Readers are encouraged to ask industry, US government and academic researchers to publish yearly benchmark carbon content values for the US grid electricity. These values can then be entered on this paper's Worksheet # 1, Line 3.
6. A 100% efficient grid electric powered HE will produce HVF with the same carbon content as the grid electricity. A less than 100% efficient HE will produce HVF with a carbon content equal to the grid electricity carbon content divided by the HE efficiency percent.
7. The FCV fleet fuel efficiency (mi/gal; L/100 km) and the carbon content of HVF determine the FCV fleet CO_2 emissions from operations. The greater the FCV fleet fuel efficiency, the lower the fleet CO_2 emissions from fleet operations. The lower the HVF carbon content, the lower the fleet CO_2 emissions from operations.
8. The FCV fleet fuel efficiency and the cost of the HVF determine the FCV fleet fuel operating expense. The greater the FCV fleet fuel efficiency, the lower the FCV fleet fuel operating expense. The lower the HVF cost, the lower the FCV fleet fuel operating expense.
9. In proposing a US FCV fleet to replace the current US ICEV fleet, it has been assumed that the HVF had no carbon content and was priced similarly to GVF. This paper demonstrates that these assumptions are not valid.

Readers can confirm these specific conclusions by reviewing the paper's narrative and worksheets.

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10. NOMENCLATURE

Abbreviation	Term
CO_2 =	carbon dioxide
FCV =	FC vehicle
FC =	fuel cell
gal =	gallon
gal-H_2 =	gallon hydrogen vehicle fuel
gas =	gasoline
GGE =	gasoline gallon equivalent
GLE =	gasoline liter equivalent
GVF =	gasoline vehicle fuel
GHG =	greenhouse gas
HHV =	high heat value
H_2 =	hydrogen
HE =	hydrogen electrolizer
HVF =	hydrogen vehicle fuel
ICEV =	ICE vehicle
ICE =	internal combustion engine
kg =	kilogram
L =	liter
L-H_2 =	liter hydrogen vehicle fuel
LHV =	low heat value
m =	meter
mi =	mile
mpg =	miles per gallon
NG =	natural gas
Nm^3 =	nominal cubic meter
O_2 =	oxygen
lb =	pound
SCF =	standard cubic foot
U/K =	unknown variable

11. AUTHOR'S BACKGROUND

Since 1990, Michael Stavy has been a Chicago based consulting energy economist with a specialization in the technical, financial, tax and political economic policy issues of renewable energy and GHG. He helps clients develop renewable energy projects; arranges private placements of debt and equity financing; analyzes how public policies effect his client's projects. When a public agency is his client, he analyzes the impact of different public energy polices.

At the 2002 Global Windpower Conference in Paris, France, he presented his paper, *The Effect That the Kyoto Protocol Will Have on the Cost of Wind Power in the Signature Countries.* In this paper Michael pointed out that the use of non-human and non-animal energy is so important to industrial societies that energy, itself, is now an additional factor of production. This was not explicitly observed in the pre-industrial era. Energy must now be added as a fourth factor to the three classical factors of economic production; land, labor and capital. Because energy is a factor of production in industrial civilization, its production and use are complicated.

In October 2002, Michael was an Invited Professor of Finance at the Ecole Supériere de Affairs (ESA) of Université Pierre Mendès France in Grenoble, France. Fall Semester 1999, he was an Adjunct Associate Professor of Finance at the University of Illinois at Chicago (UIC). During the 1997-98 Academic Year, he lectured in Finance at UIC.

Michael has an MBA from Northwestern University (Kellogg) and a BA from the UIC. In addition, he is a Illinois registered CPA. While a member (1968-1974) of the United States Army Reserve 308th Civil Affairs Group, Chicago, IL, his assignment included studying how to restore utility services to a hypothetical occupied territory.

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Worksheet #1, Levelized Cost (US$/gal-$H_2$; Euro/L-$H_2$) and Carbon Content (lb-CO_2/gal-H_2; kg-CO_2/L-H_2) of HVF Produced at a Model Wind Electric Powered 1 MW HE Plant with Benchmark Values for a Model Plant Located Next to a Model 1 MW Iowa Wind Plant

		USA		European	EUROPE Conversion to Euro and SI	
		DATA Columns		Unit	DATA Columns	
Line		Wind	Grid		Wind	Grid
1	Enter Gasoline Spot Price-US$/Gal	$0.82	$0.82	Euro/L-gasoline→	0.18	0.18
2	Enter HE Capital Cost-US$/MW	$1,000,000	$1,000,000	Euro/MW→	842,460	842,460
3	Enter Yr Aver. CO_2 Emissions-lb/MWh US Gen. Mix	1,351	1,351	CO_2-kg/MWh US Gen. Mix	612.6	612.6
4	Constant MWh/gal-H_2	0.036362	0.036362	MWh/L-H_2	0.00961	0.00961
5	Enter Electricity Cost-US$/MWh	$40	$40	Electricity Cost-Euro/MWh	33.70	33.70
6	Enter Wind Electricity-%	100%	35%	Wind Electricity-%	100%	35%
7	Enter Annual Fixed O&M-% Line 2	3%	3%	Annual Fixed O&M-% Line 2	3%	3%
8	Enter Variable O&M- US$/gal-$H_2$	$0.15	$0.15	Variable O&M- Euro/L-H_2	0.033	0.033
9	Enter Physical Life of HE-Years	25	25	Physical Life of HE-Years	25	25
10	Enter Interest/ROI Rate-%	10%	10%	Interest/ROI Rate-%	10%	10%
11	Computed Capital Amortization Factor-CAF	0.11017	0.11017	Capital Amortization Factor-CAF	0.11017	0.11017
12	Enter HE Capacity Factor-%	35%	100%	HE Capacity Factor-%	35%	100%
13	Enter HE Efficiency Factor-%	80%	80%	HE Efficiency Factor-%	80%	80%
14	Computed H_2 Produced per Year-gal-H_2/yr	67,455	192,729	H_2 Produced per Year-L-H_2/yr	255,317	729,478
15	Computed Annual Amortization Cost-US$/yr	$110,168	$110,168	Annual Amortization Cost-Euro/yr	92,812	92,812
16	Computed Annual Fixed O&M Cost-US$/yr	$30,000	$30,000	Annual Fixed O&M Cost-Euro/yr	25,274	25,274
17	Computed Levelized Annual Cost-US$/gal-$H_2$	$2.07795	$0.72728	Levelized Annual Cost-Euro/L-H_2	0.46251	0.16188

Worksheet #1 Continued

Line		USA DATA Columns Wind	 Grid	European Unit	EUROPE Conversion to Euro and SI DATA Columns Wind	 Grid
18	Transferred Levelized Annual Cost-US$/gal-$H_2$ From L.17	$2.08	$0.73	Levelized Annual Cost-Euro/L-H_2 From L.17	0.46	0.16
19	Transferred Variable O&M cost-US$/gal-$H_2$ From Line 8	$0.15	$0.15	Variable O&M cost-Euro/L-H_2 From L. 8	0.03	0.03
20	Computed Electricity Cost-US$/gal-$H_2$	$1.82	$1.82	Electricity Cost-Euro/L-H_2	0.40	0.40
21	Computed Total Levelized Cost-US$/gal-$H_2$	$4.05	$2.70	Total Levelized Cost-Euro/L-H_2	0.90	0.60
22	Transferred Gasoline Spot Price-US$/Gallon From Line 1	$0.82	$0.82	Gasoline Spot Price-Euro/L	0.18	0.18
23	Computed Levelized Cost (above) below Spot Price-US$/gal	($3.23)	($1.88)	Cost (above) below Spot Price-Euro/L	(0.72)	(0.42)
24	Computed CO_2 Emissions-lb/gal-H_2	0.0	40.2	CO_2 Emissions-kg/L-H_2	0.0	4.8

Worksheet # 2, A Comparison of Carbon Emissions (lb-CO_2/100mi; kg-CO_2/100km;) and Fuel Costs (US$/100mi; Euro/100km) of the Current US Passenger ICEV Fleet with a Proposed US Passenger FCV Fleet

Line		USA DATA Columns		European Unit	EUROPE Conversion to Euro and SI DATA Columns	
		ICEV	FCV		ICEV	FCV
A	Enter FCV HE CO_2 Emissions-lb-CO_2/gal-H_2	xx	40.2	HE kg-CO_2/L-H_2	xx	4.8
B	Enter Fuel Cost-ICEV $/gal-gasoline [FCV $/gal-$H_2$]	$0.82	$2.70	Fuel Cost Euro/L-gasoline [Euro/L-H_2]	0.18	0.60
C	Enter ICEV Fleet [FCV Fleet]-Aver. mi/gal	21.5	21.5	L/100km	10.9	10.9
D	Enter ICE US ICEV Fleet Aver. CO_2 Emissions-lb-CO_2/mi	0.9160	xx	kg-CO_2/km	0.2582	xx
E	Computed [FCV Fleet CO_2 Emissions-lb-CO_2/mi]	xx	1.8698	kg-CO_2/km	xx	0.5270
F	Compare ICEV verse [FCV] Emissions, lb-CO_2/100mi	91.6	187.0	kg-CO_2/100km	25.8	52.7
G	Computed ICEV CO_2 Emissions-lb-CO_2/gal-gasoline	19.7	xx	kg-CO_2/L-gasoline	2.4	xx
H	Compare ICEV lb-CO_2/gal-gasoline vs [FCV lb-CO_2/gal-H_2]	19.7	40.2	kg-CO_2/L-gasoline [kg-CO_2/L-H_2]	2.4	4.8
I	Computed ICEV Fleet verse [FCV Fleet] Fuel Cost to Drive US$/100mi	$3.81	$12.56	Euro/100km	2.00	6.57