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Integrated Renewable Hydrogen Utility System

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Abstract

An integrated system consisting of the combined electrolyzer and fuel cell units with hydrogen storage has been depicted. The system provides continuous power supply from intermittent renewable power sources. An analysis of system's application and economics has shown that the electrolyzer would operate with a low capacity factor dictated by the capacity factor of the renewable power source, and the fuel cell would have a capacity factor of about 50%. Because of the low capacity factors and relatively low round trip efficiency (about 50%) the cost of electricity produced and delivered by the system is several times higher than the cost of the electricity from the renewable source. This is the price for convenience of having the power from the renewable source available constantly. This may be acceptable for some applications.

Introduction

The fuel cells have a tremendous market potential in automotive, marine and space applications, as in portable and stationary power generation. Each market segment has its own requirements including the cost at which it would be possible to penetrate the market. Although most of the PEM fuel cell development efforts are directed toward automotive applications, earlier market penetration may be feasible in other market segments. In particular, market opportunities have been identified in residential power supplies rated at 2-10 kW, off-grid or grid integrated. The biggest obstacle in reaching this market is fuel availability. PEM fuel cells run on relatively pure hydrogen, which is not readily available. One approach is to use natural gas and reform it before using it in fuel cells. Each fuel cell unit therefore must be equipped with a fuel processor. The first prototype of an integrated natural gas fueled fuel cell system has been completed and is currently being tested in Energy Partners laboratories. A pre-production prototype (or prototypes) will be developed next and tested in real-life application.

Another option to provide hydrogen fuel for PEM fuel cells would be to use renewable energy sources for hydrogen generation. Such a system would increase potential markets for stationary fuel cell power systems since it would not have to be tied to either the power grid or natural gas supply line. It may be used to provide both electricity and fuel in remote locations and on islands. Since such a system would generate absolutely zero emissions it may be suitable for ecologically sensitive areas, such as national parks. In addition, the system may also be used for power storage and load leveling for renewable power plants, such as solar, wind, hydro-electric or geothermal power plants.

The proposed integrated hydrogen energy system would consist of an electrolyzer, hydrogen and oxygen storage systems, fuel cell system and controller/power conditioning unit (Figure 1). The system must be connected with a renewable power source, such as a photovoltaic array, solar thermal power plant, wind turbine, ocean current turbine-generator, small hydro power plant, or geothermal power plant. The system uses excess electrical power, during periods when power generation exceeds power demand, to produce hydrogen and oxygen. The electrolyzer will be a proton exchange membrane type capable of operating at high pressure (800-1000 psig). Hydrogen and oxygen produced will be stored in pressure tanks at pressures up to the electrolyzer operating pressure (800-1000 psig), so that no additional compression will be needed. During periods when the power demand exceeds power production from renewable energy sources, power will be produced by the fuel cell. The fuel cell may operate with either pure oxygen (which will be available from the electrolysis process) or air at an operating pressure of up to 50 psig (4.5 bar), and operating temperature up to 80°C.

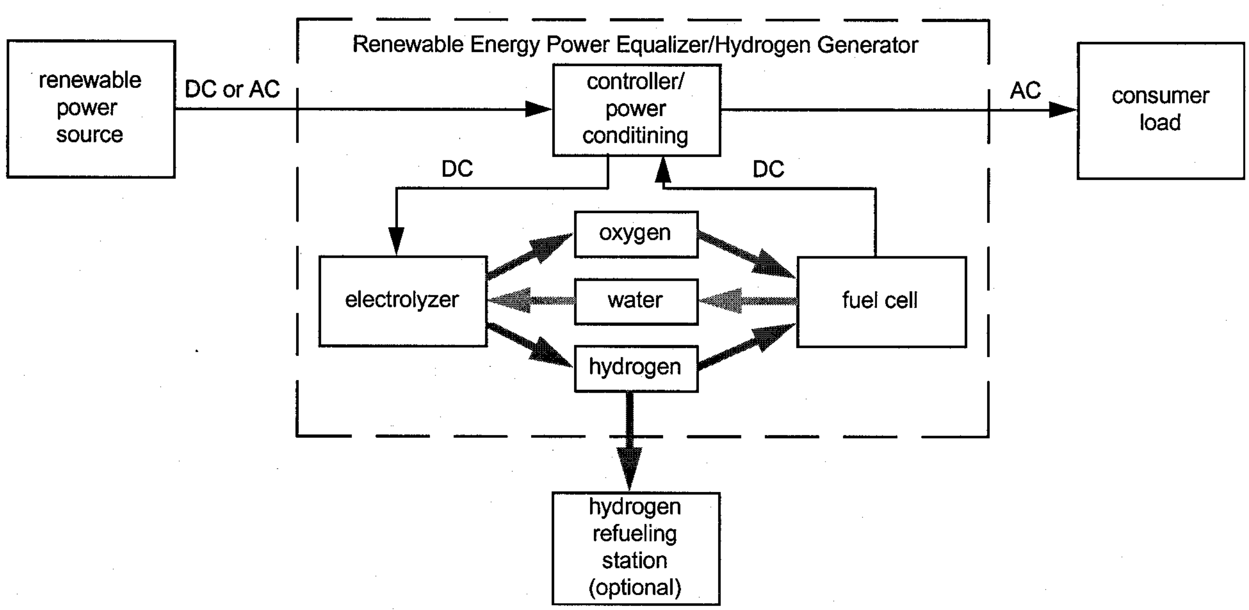

Figure 1 Proposed Integrated Renewable Hydrogen Fuel Cell Power System

The supporting systems include handling of the produced/reactant gases and water, heat management system, and controls and power conditioning. Handling of the product/reactant gases includes the control of flow rate, pressure, temperature and humidity. Product water from the fuel cell is used as a feed for the electrolyzer, as well as a cooling medium. The heat management system serves both the electrolyzer and fuel cell. This includes a tank, pump, filter(s), heat exchanger(s), piping, and controls.

The controller/power conditioning unit (CPCU) has a crucial role in operation of the system. The main role is to manage the output of the renewable power source in order to provide a regulated supply of AC current to the consumer load at all times. The renewable power source may generate either DC (photovoltaic array) or AC (wind, hydro or geothermal power plant). In the former case the CPCU will have to be designed to regulate the voltage of the renewable power source and match it to the electrolyzer operating voltage, and to regulate the renewable power source and fuel cell DC and convert it to AC to be delivered to the consumer load. In the latter case the CPCU will have to be designed to forward AC from the renewable power source to the consumer. Excess AC from the renewable power source will be converted into DC with voltage matching that of the electrolyzer. The fuel cell power output (DC) will be converted into usable AC and delivered to the consumer load. The CPCU will also handle the control and monitoring of the fuel cell and electrolyzer operational envelopes.

An additional advantage of this system is hydrogen and oxygen availability for other applications. Hydrogen may be used as fuel for various vehicles (on-road and off road vehicles and boats), and oxygen may have application in research labs, water treatment, hospitals, and even in homes (for enhanced air quality and breathing).

Application Analysis

The following analysis of an idealized case has been perform in order to get an idea on relative nominal power inputs and outputs, system efficiencies and capacity factors which will then be used in the economic analysis.

For the electrolyzer/fuel cell system these parameters are related to each other. The relative nominal power outputs and capacity factors are dictated by the power profiles of both the available power source and load. This will vary from location to location and from application to application. In general, renewable sources, such as solar and wind, are available intermittently with daily and seasonal variations. The integrated renewable hydrogen utility system is supposed to use power from a renewable source and deliver it to the load either directly or indirectly.

In general there are three modes of operation of the system, as shown in Figure 2:

- during periods when renewable power is not available – power to the load is provided by the fuel cell
- during periods when renewable power is available but not sufficient to cover the load – power to the load is provided from both source and fuel cell
- during periods when renewable power exceeds load – power to the load is provided directly from the source and excess (if any) is used by the electrolyzer to generate hydrogen

The source power profile is assumed to have a sinusoidal form typical for solar power availability and the load was assumed to be constant (Figure 2). Energy from the renewable power source, E_S, must be sufficient to cover the load plus (E_L) all the losses in energy conversions:

$$E_S = E_{ELZ} + E_{S\text{-}L} \quad \text{(Eq. 1)}$$

$$E_{FC} = E_{ELZ}\eta_{ELZ}\eta_{FC} \quad \text{(Eq. 2)}$$

$$E_L = E_{FC} + E_{S\text{-}L} \quad \text{(Eq. 3)}$$

where:

E_S = energy from the source
$E_{S\text{-}L}$ = energy from the source used directly by the load
E_L = energy consumed by the load
E_{ELZ} = energy consumed by the electrolyzer
E_{FC} = energy produced by the fuel cell
η_{ELZ} = electrolyzer efficiency
η_{FC} = fuel cell efficiency

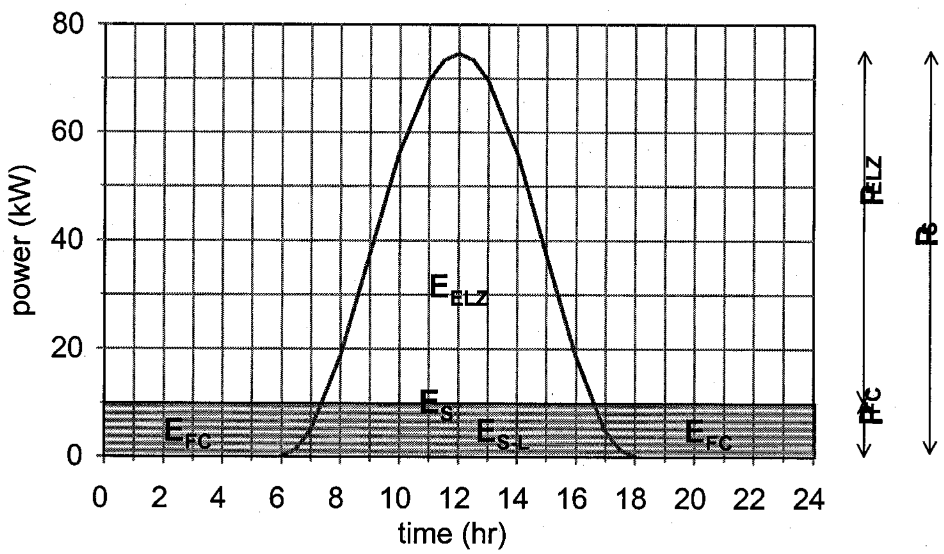

Figure 2 Idealized source and load profiles

For sizing purposes it is interesting to know the ratio between the electrolyzer and fuel cell power. Figure 3 shows this ratio as a function of fuel cell and electrolyzer efficiencies. In general, the higher fuel cell and electrolyzer efficiencies are less energy is needed from the source and consequently the lower electrolyzer power is required. For the range of analyzed fuel cell and electrolyzer efficiencies (0.45-0.55 and 0.75-0.85 respectively) the electrolyzer's nominal power varies from 7.5 to 5.6 times the fuel cell nominal power. This is actually the maximum ratio that can be expected because of the assumed constant load. In the cases with a variable load this electrolyzer/fuel cell power ratio may be considerable smaller, but the fuel cell capacity factor would be considerably lower.

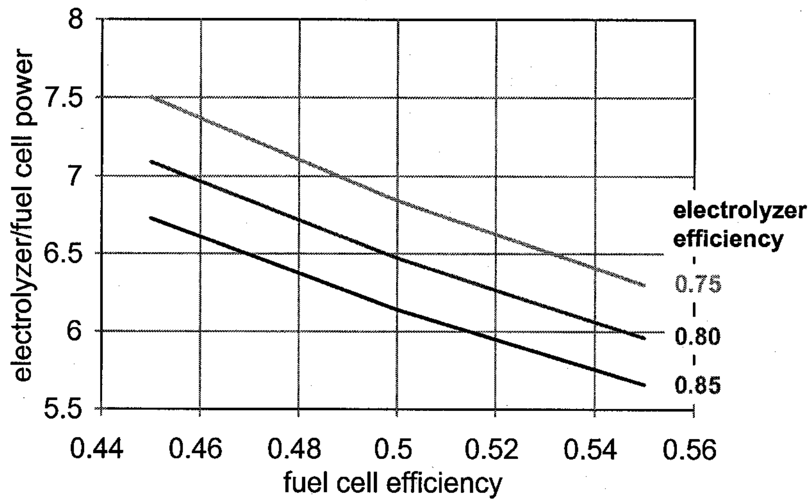

Figure 3 Electrolyzer/fuel cell power ratio

The fuel cell capacity factor is defined as ratio of actually produced electricity in a given time period (in this case 24 hours) and electricity that could have been produced if the fuel was operated full power during the same time period:

$$CF_{FC} = \frac{E_{FC}}{24 \cdot P_{FC}} \qquad \text{(Eq. 4)}$$

Similarly, the electrolyzer capacity factor is defined as ratio of actually consumed electricity by the electrolyzer in a given time period and electricity that could have been consumed if the electrolyzer was operated full power during the same time period:

$$CF_{ELZ} = \frac{E_{ELZ}}{24 \cdot P_{ELZ}} \qquad \text{(Eq. 5)}$$

Figure 4 shows that both the fuel cell and the electrolyzer capacity factors are fairly independent of the fuel cell and electrolyzer efficiencies, and for this case the fuel cell capacity factor was about 58% and the electrolyzer capacity factor was about 22.5%. Because of the assumed constant load this is actually the highest fuel cell capacity factor possible with the assumed source power profile. The electrolyzer capacity factor is very low, and it can be increased in the cases where more load can be satisfied directly from the source.

The total system efficiency may be defined as a ratio between produced and consumed energy:

$$\eta_{SYS} = \frac{\text{energy out}}{\text{energy in}} = \frac{E_L}{E_S} \qquad \text{(Eq. 6)}$$

The resulting system efficiency is shown in Figure 5. As expected it is a strong function of fuel cell and electrolyzer efficiencies. It is higher than the round-trip conversion efficiency ($\eta_{fc}\eta_{elz}$) because a part of the delivered energy comes directly from the source (power conditioning losses, if any, have been neglected in this analysis).

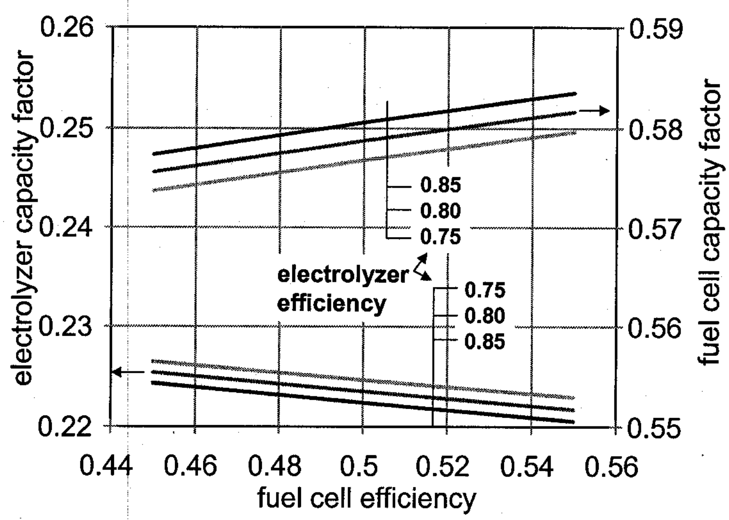

Figure 4 Electrolyzer and fuel cell resulting capacity factors

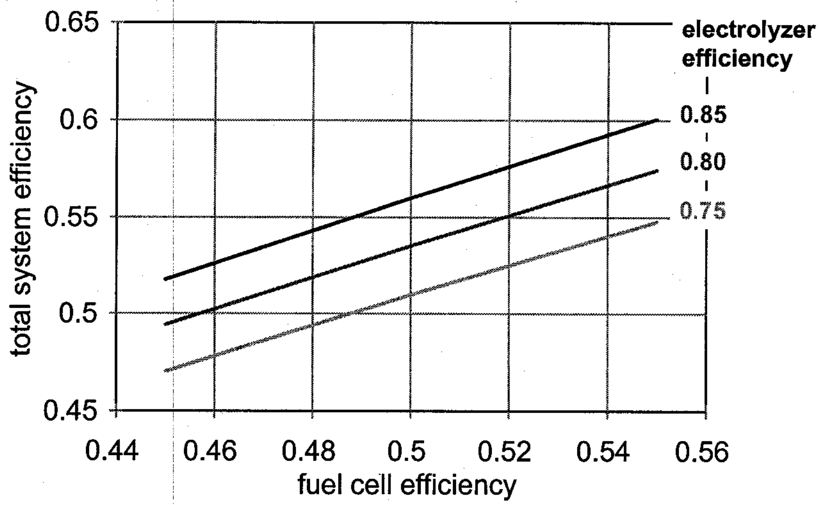

Figure 5 Resulting total system efficiency

Cost Analysis and Operating Voltage Optimization

Both the fuel cell and the electrolyzer have the feature that the efficiency may be increased by adding more cells. In fuel cell, this results in increased cell voltage for a given power output, and therefore in increased efficiency. In electrolyzer, this results in lower cell voltage which again results in increased efficiency. Increased efficiency of both fuel cell and electrolyzer means lower operating costs. However, additional cells mean higher capital cost. Therefore, there must be an optimum fuel cell and electrolyzer voltage that would result in the lowest total cost, i.e., cost of delivered electricity in $/kWh.

Equations

Cost of delivered electricity (in $/kWh) is the total annual cost consisting of annualized capital cost (ACC) and annual operating cost (AOC), divided by the total annual amount of electricity delivered (AED):

$$C_{el}^{out} = \frac{ACC + AOC}{AED} \qquad \text{(Eq. 7)}$$

Annualized capital cost is:

$$ACC = FCR \cdot (CC_{fc} + CC_{elz}) \qquad \text{(Eq. 8)}$$

where:
FCR = fixed charge rate (yr^{-1})
CC_{elz} = electrolyzer capital cost
CC_{fc} = fuel cell capital cost

$$CC_{fc} = (C_{stack} + C_{cell} \cdot N_{cell})_{fc} \qquad \text{(Eq. 9)}$$

where:
C_{stack} = fixed cost per fuel cell stack
C_{cell} = cost per cell
N_{cell} = number of cells in the stack

$$N_{cell}^{fc} = \frac{P_{fc} \cdot 1000}{V_{cell}^{fc} \cdot i_{fc} \cdot A_{fc}} \qquad \text{(Eq. 10)}$$

where:
P_{fc} = fuel cell nominal power (kW)
i_{fc} = fuel cell current density at nominal power (A/cm^2)
A_{fc} = fuel cell active area (cm^2)
V_{cell}^{fc} = fuel cell cell voltage at nominal power (V);
in this analysis the polarization curve has been approximated by a linear relationship:

$$V_{cell}^{fc} = V_o^{fc} - k_{fc} \cdot i_{fc} \qquad \text{(Eq. 11)}$$

where:
V_o = polarization curve intercept voltage (V)
k = polarization curve slope (V/A)
i_{fc} = fuel cell current density (A/cm^2)

Electrolyzer capital cost is:

$$CC_{elz} = (C_{stack} + C_{cell} \cdot N_{cell})_{elz} \qquad \text{(Eq. 12)}$$

where:
C_{stack} = fixed cost per electrolyzer stack
C_{cell} = cost per cell
N_{cell} = number of cells in the stack

$$N_{cell}^{elz} = \frac{P_{elz} \cdot 1000}{V_{cell}^{elz} \cdot i_{elz} \cdot A_{elz}} \quad \text{(Eq. 13)}$$

where:
P_{elz} = electrolyzer nominal power (kW)
i_{elz} = electrolyzer current density (A/cm^2)
A_{elz} = electrolyzer cell active area (cm^2)
V_{cell}^{elz} = electrolyzer cell voltage (V)

$$V_{cell}^{elz} = V_o^{elz} + k_{elz} \cdot i_{elz} \quad \text{(Eq. 14)}$$

where:
V_o = polarization curve intercept voltage (V)
k_{elz} = polarization curve slope (V/A)
i_{elz} = electrolyzer current density (A/cm^2)

From Equations 2, 4 and 5, the electrolyzer nominal power is:

$$P_{elz} = \frac{P_{fc} CF_{fc}}{CF_{elz}} \frac{V_{cell}^{elz}}{V_{cell}^{fc}} \quad \text{(Eq. 15)}$$

where:
P_{fc} = fuel cell nominal power (kW)
CF_{fc} = fuel cell capacity factor
CF_{elz} = electrolyzer capacity factor
V_{cell}^{fc} = fuel cell cell voltage (V)
V_{cell}^{elz} = electrolyzer cell voltage (V)

Annual operating cost is:

$$AOC = \frac{AED}{\eta_{fc}\eta_{elz}} C_{el}^{in} \quad \text{(Eq. 16)}$$

where:
AED = annual amount of electricity delivered (kWh/yr)
η_{fc} = fuel cell efficiency
η_{elz} = electrolyzer efficiency
C_{el}^{in} = cost of electricity from renewable source (\$/kWh)

Annual amount of electricity delivered (kWh/yr)

$$AED = P_{fc} \cdot CF_{fc} \cdot 8760 \quad \text{(Eq. 17)}$$

where:
P_{fc} = fuel cell nominal power (kW)
CF_{fc} = fuel cell capacity factor
8,760 = hours/yr

Inputs, assumptions and variables

The optimization analysis was performed with the following set of assumptions:

- fuel cell polarization curves: linearized from Energy Partners data (V_o= 0.97, k = 0.275)
- electrolyzer polarization curve: linearized from Treadwell data (V_o= 1.6, k = 0.24)
- fixed charge rate (capital recovery factor): 0.15/yr (corresponding to lifetime of 10 years and discount rate of 7.5%)
- fuel cell capacity factor: 0.58
- electrolyzer capacity factor: 0.22
- fuel cell nominal power output: 10 kW
- only fuel cell and electrolyzer costs were taken into account

The following parameters were used as variables:

- fuel cell present cost (based on 300 cm^2 active area):
  - fixed cost per stack: $8,000
  - cost per cell: $800
  - total costs corresponding to about $5,000/kW
- fuel cell future cost (based on 300 cm^2 active area):
  - fixed cost per stack: $1,700
  - cost per cell: $170
  - total costs corresponding to about $1,000/kW
- fuel cell mass production cost (based on 300 cm^2 active area):
  - fixed cost per stack: $200
  - cost per cell: $10
  - total costs corresponding to less than $100/kW
- electrolyzer present cost (based on 200 cm^2 active area):
  - fixed cost per stack: $8,000
  - cost per cell: $800
- electrolyzer future cost (based on 200 cm^2 active area):
  - fixed cost per stack: $2,000
  - cost per cell: $200
- fuel cell nominal cell voltage: 0.6V – 0.8 V
- electrolyzer nominal cell voltage: 1.8V – 2.2V
- cost of electricity from renewable source: $0.02-$0.20/kWh

Results and discussion

At current fuel cell and electrolyzer costs, the cost of delivered electricity is prohibitively expensive:

- about $1/kWh if the cost of input electricity is $0.20/kWh
- $0.5/kWh if the cost of input electricity is $0.05/kWh, and
- $0.4/kWh if the cost of input electricity is $0.02/kWh.

The resulting electricity cost is lower for the projected/future fuel cell and electrolyzer capital costs:

- about \$0.60/kWh if the cost of input electricity is \$0.20/kWh
- \$0.21/kWh if the cost of input electricity is \$0.05/kWh (Figure 6), and
- \$0.13/kWh if the cost of input electricity is \$0.02/kWh.

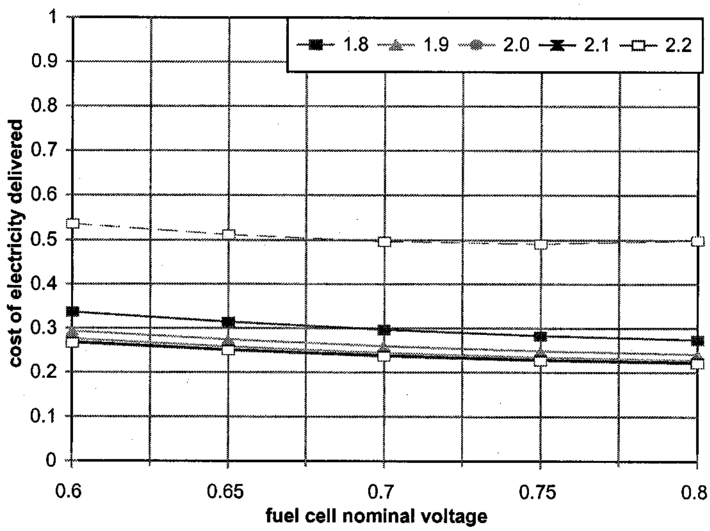

Figure 6 Cost of delivered electricity as a function of fuel cell nominal voltage (x-axis) and electrolyzer nominal voltage (legend) for future costs scenario and cost of electricity from renewable power source \$0.05/kWh (dashed line corresponds to the lowest cost for the current cost scenario)

Optimum fuel cell and electrolyzer voltages are about 0.7-0.8V/cell for the fuel cell and 2.0-2.2V/cell for the electrolyzer. The total cost is less sensitive to the selected nominal operating voltage. As shown in Figure 7, the cost of input electricity, even at \$0.02/kWh is the highest contributing factor to the cost of delivered electricity.

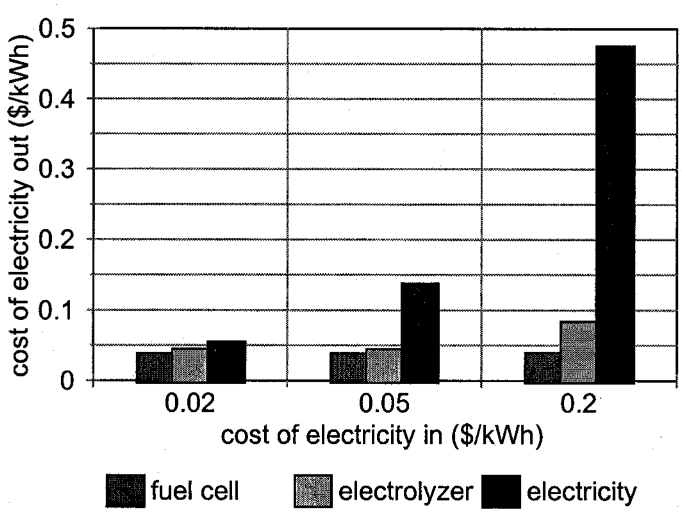

Figure 7 Breakdown of the cost of delivered electricity for future costs scenario

Figure 8 shows almost linear relationship between the cost of input electricity and the cost of delivered electricity for the two cases, namely present and future fuel cell and electrolyzer costs. An additional scenario is added in which the fuel cell cost is assumed to be as low as required for automotive applications (>$100/kW). However, this scenario does not reduce the cost of delivered electricity significantly. This is due to the electrolyzer's high costs and low capacity factor. It should be noted that the extremely low fuel cell scenario is likely if (or when) the fuel cells are mass produced for automotive applications. Unfortunately, there is no similar scenario for the electrolyzers.

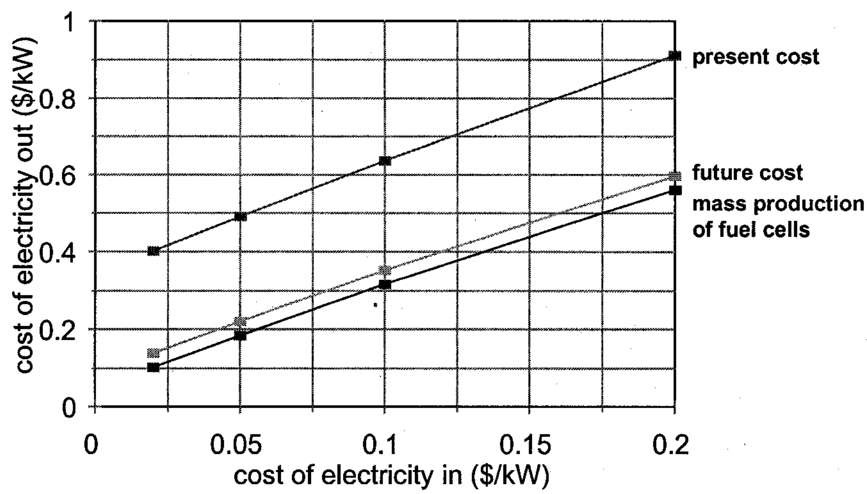

Figure 8 Cost of delivered electricity as a function of the cost of electricity input from the renewable power source for different scenarios

Conclusions

Based on the results of the analyses presented above the following conclusions may be reached:

- The integrated renewable hydrogen utility system is technically feasible. It delivers power to the users when it is needed. As an extra bonus (which was not included in the above analysis), both hydrogen and oxygen that are generated in the process may have commercial use and value (hydrogen as a transportation fuel and oxygen for water treatment, in hospitals or in research facilities).
- Power supply in remote areas and on isolated islands has been identified as a potential market, with three different power levels 1 kW, 10, kW and up to 100 kW..
- The system does not make any impact on the environment – it generates no emissions and it generates no noise. As such it may be used for power supply in environmentally sensitive areas, such as national parks.

- The round-trip efficiency (electrolyzer and fuel cell) is about ~40%. This relatively low efficiency makes it difficult to compete with other methods of energy storage, such as batteries, particularly for short term storage.
- The cost of electricity out can be several times higher than the cost of electricity in because of low round-trip efficiency, low capacity factors and relatively high capital costs. This limits application to the cases that can justify high cost of around-the-clock electricity availability.
- The electrolyzer power is several times higher than the fuel cell power. This is related to the renewable source availability and the system inefficiency.
- The electrolyzer has a very low capacity factor (about 22%), which has a significant impact on the cost of electricity. Commercial usage of hydrogen (and potentially oxygen) may increase the electrolyzer's capacity factor and improve the system's economics. (The cost of hydrogen refueling station must then also be taken into account).
- An air fuel cell would be at least twice as big as oxygen fuel cell. An oxygen fuel cell is more efficient (up to 75% at partial load). A detailed cost analysis is required that would take into account the capital cost of the fuel cell and blower on one side and oxygen storage and oxygen recirculation pump on the other side, as well as the efficiencies of the systems to be compared. Safety of oxygen storage must also be taken into account.
- The lowest electricity cost results with a high fuel cell operating voltage, which requires a large but efficient fuel cell stack.
- The lowest electricity cost results with a high electrolyzer voltage, thus less efficient but more compact electrolyzer stack. This is due to electrolyzer's high capital cost and low capacity factor.
- The automotive market may bring down the cost of fuel cells because of mass-production. Unfortunately, no such market may be envisioned for the electrolyzer, which implies that the cost of the electrolyzer would remain to be a problem, particularly having in mind heavy Pt catalyst loading and extensive use of expensive materials, such as Nb and Zr.
- In order to alleviate the problem of high electrolyzer capital cost and low capacity factor, it definitively makes sense to investigate the possibility of a reversible fuel cell, i.e., combine the functions of fuel cell and electrolyzer in a single unit. Based on preliminary analyses, it seems that there is a good match between the electrolyzer and fuel cell size (in terms of active area, current density and number of cells).