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LOW COST, HIGH EFFICIENCY REVERSIBLE FUEL CELL (AND ELECTROLYZER) SYSTEMS

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Abstract

A reversible solid-oxide fuel cell (SOFC)/electrolyzer system capable of storing electrical energy generated from renewable sources at projected round-trip efficiencies over 80% and providing backup power generated from propane at efficiencies over 60% (LHV) was studied. The systems perform all electrochemical functions using a single stack assembly with a unique systems design that stores both gases and thermal energy. Total system capital and operating costs are projected to be lower than an equivalent lead-acid battery with a backup generator system. This work was a follow-on to experimental work funded under NASA SBIR Phase I and II programs.

Introduction

Grid-independent electric power systems using renewable power sources (such as solar, wind, and water) can potentially drastically reduce CO_2 emissions while offering siting flexibility and economic advantages. Cost is the major barrier to the practical use of systems of this type. Because power is generated intermittently and is variable -- the nature of renewable generation -- such systems typically require both a large energy storage capacity and a backup generator. Practical choices to meet these requirements are deep-cycle lead acid batteries for storage plus an engine generator. While batteries can achieve high energy storage efficiencies near 80%, the battery/generator combination is quite expensive (first cost plus maintenance costs). In addition, current generators using internal combustion technology are highly polluting, noisy, and have low fuel efficiencies.

Fuel cell technologies are described in the 2001 DOE Hydrogen Program Annual Operating Plan as "cost effective, highly efficient, and critical for overall success in the Hydrogen Program Strategic Plan." As shown in Figure 1, fuel cells serve as both a transitional technology -- as the world moves away from fossil fuels, and as an end point technology -- for the efficient production and utilization of hydrogen.

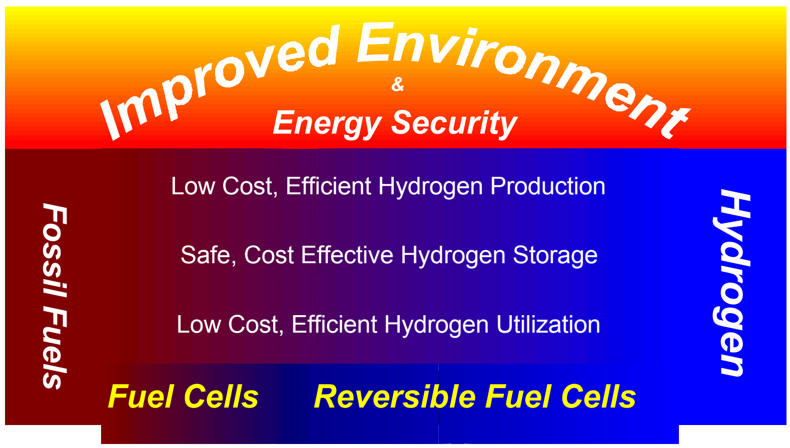


Figure 1. Fuel Cells as a Transition Technology as Described in the DOE Hydrogen Program Strategic Plan.

The Reversible TMI Solid Oxide Fuel Cell (SOFC) Systems

The TMI reversible system employs a high-temperature, solid oxide-based electrochemical process to produce electricity from common hydrocarbon fuels (e.g., natural gas, propane and bio-derived fuel) as well as hydrogen. Operated in electrolyzer mode, the TMI reversible system uses electricity and thermal energy to convert pure water into fuel (hydrogen and oxygen). Heat is a byproduct of all high temperature fuel cells. However, compared to other fuel cells that operate at low temperature (e.g., proton exchange membrane (PEM)), the TMI reversible system can use the waste thermal energy produced during electricity generation mode to achieve high systems efficiency in electrolyzer mode, ultimately lowering product life cycle costs for the combined system. Low cost is a stated goal of the DOE Hydrogen Program.

Specific potential advantages of high temperature SOFC systems over lower temperature systems include:

1. Higher potential “round trip” energy storage efficiency (80% vs. 65%)
2. High fuel-to-electricity efficiency using common fuels instead of hydrogen

3. Lower costs due to reduced part count and increased efficiency.
4. Higher reliability because of modular scalable designs.

At the cell level, the SOFC uses the high operating temperatures (~800°C) of SOFCs to improve electrode kinetics, making low electrode polarization voltages possible. By using steam rather than liquid water for electrolysis, a smaller Gibbs Free Energy change is required, resulting in higher overall system efficiency. Key to this is the capture of heat during fuel cell operation and retention for use later to offset the total energy required by the electrolysis process. Additionally, the high quality exhaust heat can be used to pre-process carbonaceous fuels, adding to overall efficiency if and when these fuels are used.

Scope of Work

The scope of the "Low Cost, High Efficiency Reversible Fuel Cell Systems" project focused on the economic impact of a small scale reversible TMI fuel cell system module in a wind-coupled, grid independent, residential power application. This focus also included comparisons with other varieties of renewable systems in the same configuration, since most economic analyses in the literature are derived from larger size configurations that benefit from economies of scale. The work also included some laboratory tests to demonstrate cell performance characteristics consistent with extensive experimental work performed previously by TMI under NASA SBIR Phase I and II studies in 1998-99. This previously funded work demonstrated actual operation of the reversible TMI cell design and provided data showing the feasibility of very high system efficiencies.

Results

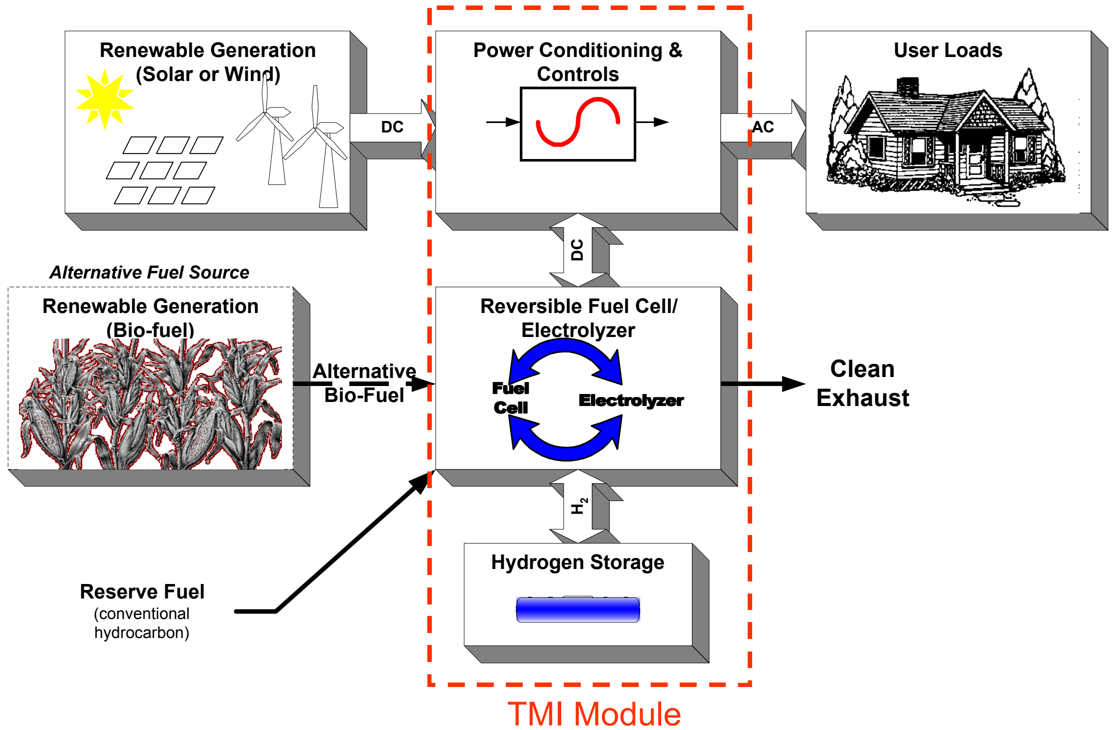
Engineering Cost Study

For this study, TMI performed the conceptual design and simulations of a configuration based on the TMI reversible solid oxide fuel cell/electrolyzer system using hydrogen for energy storage and backup power generation from propane and ambient air. The main system components included an electrolyzer (for generation/storage of H_2), a fuel cell (for conversion of stored H_2 back into electricity), and a back-up generator producing electricity from propane. Figure 2 shows how this design concept can be retrofitted to use existing wind-based technology.

Design Considerations

The analysis assumed hydrogen is stored as a gas at near-ambient temperature, an energy storage efficiency (electrical energy out/electrical energy in) near 80% (similar to lead acid batteries), and a system efficiency near 60% (LHV) when using propane, with negligible air pollutant emissions. All thermal, electrical, and chemical energies were considered and it was assumed that thermal energy spontaneously flows only from higher to lower temperature. All electrochemical and thermal processes are performed under conditions as close to equilibrium as practical. Based on prior experimental work by TMI, electrochemical $H_2/O_2/H_2O$ cells were assumed to operate with only small differences between electrolysis and fuel cell voltages.

(a) Reversible Fuel Cell/Electrolyzer



(b) Traditional System

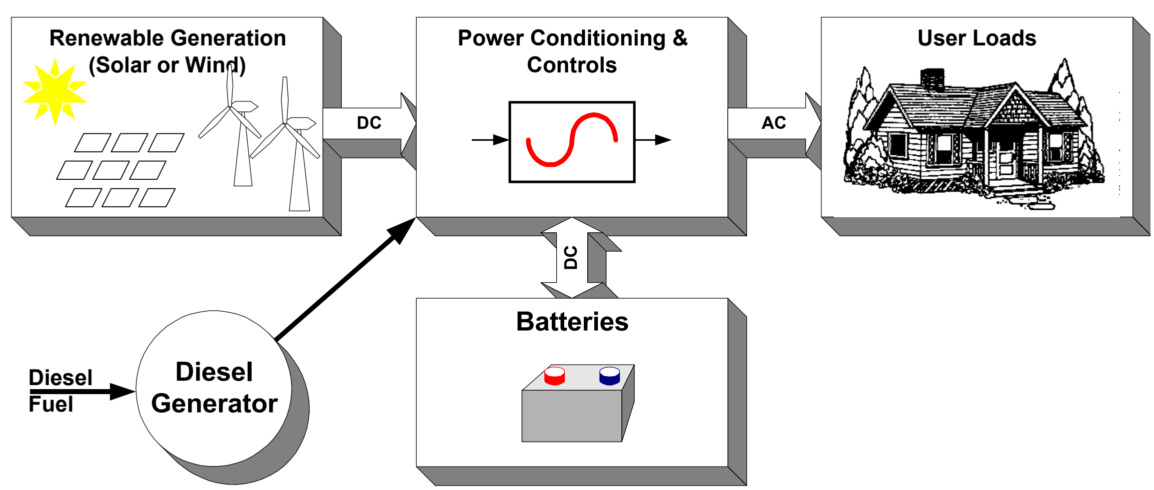


Figure 2. Reversible Fuel Cell System Compared to Existing Designs

Example Requirements Summary

This case study is based on a hypothetical residence of 2500 square feet at a remote site near Boulder, Colorado. The assumed power requirements are limited to 120 volts AC, 60 Hertz, single phase with good power quality needed (true sine wave with low total harmonic distortion, good voltage and frequency regulation) for computers, home entertainment, noise minimization, and other reasons. A high degree of reliability was also deemed to be essential (system outages being very infrequent and brief). The residence was assumed to use propane fuel for all significant heating needs: space heating, cooking, hot water, and clothes dryer. The residence has no air conditioning, but does use cooling fans (and possibly evaporative coolers) and most types of small kitchen and household appliances. The maximum instantaneous peak AC demand (to handle motor starting, etc.) is 3000 Watts and 4000 Volt-Amperes (VA).

The assumed average daily AC net power usage (averaged over 365 days) was 15,360 Watt-hours/24 hr (an average of 640 Watts and a total of 5606 kWh/year). This average usage is about 85% of the assumed worst case day. Dividing 640 Watts by the specified system peak capacity of 3000 Watts is an annual load factor of 21.3%. This value is typical for residences without air conditioning.

The assumed average cost of propane fuel is $1.00 per gallon delivered, including tank rental charges for propane (also called liquefied petroleum gas or LPG). Its lower heating value (LHV) is assumed to be 84,300 BTU/gallon. This calculation equals a cost of $11.86 per million BTU. In comparison, if diesel fuel is assumed to cost $1.50 per gallon delivered with a LHV of 128,000 BTU/gal., an equivalent dollar cost per million BTU is $11.72 (1999 price estimates).

Reversible Fuel Cell/Electrolyzer Assumptions

The proposed reversible system for the above case provides both energy storage (using H_2) and backup generation from propane fuel. The system utilizes four (4) identical reversible fuel cell/electrolyzer modules having preliminary specifications as described in Table 1.

Each module contains the following components:

- solid oxide stack
- hydrogen gas storage system
- liquid water storage system
- multifunction power conditioning circuit
- small lead-acid battery (for instantaneous load following)
- balance of system components, including compact heat exchangers, pump, blowers, valves, insulation, startup heater, control system, sensors, enclosure, etc.

Comparisons

Five cases were considered in detail (using estimated 2009 selling prices for the new-technology systems) and are summarized in Figure 3. The installed costs in the table were computed using a system peak power requirement of 3.0 kW, an average annual power requirement of 640 W/day, and rounding to the nearest $100. Although the example application used in this report is based upon a moderate-sized residence, most of the considerations cited also apply to smaller and larger systems having average power requirements anywhere from about 500 to at least 5000 Watts. New technologies recommended are applicable to both new installations and upgrades of existing systems.

Table 1. Module Specifications

Parameter	Value	Units
Nominal Output Power	1000	Watts
Maximum Surge Power	4800	VA
Nominal Energy Storage	6500	Wh
Output AC Voltage (60 Hz)	120	Volts rms
Typical Net Propane Efficiency	62%	LHV
Typical Energy Storage Efficiency	81%	Wh
Noise @ 1 meter	< 50	DbA
Retail Price (est. 2009)	$3400.	
Average Annual Maintenance	$170.	

Each case had advantages and disadvantages depending on the objectives. For maximum reduction in pollution, the renewable wind and wind-hybrid systems (both with and without reversible fuel cells) offer the lowest CO_2 emissions. The diesel generator system is available 'today' but when factors such as load leveling and maintenance are included, this system appears to be poorly suited for year round off-grid applications.

Reversible Fuel Cell Experiments

The main advantage of the SOFC is its potential for high reversible efficiency. However, this assumes the capability to store and recycle thermal energy. Thus, reversible cell operation in a single device requires completion of a key development to enable electrochemical processes to occur at similar temperatures, and thereby mitigate thermodynamically undesirable steps.

As part of this program, TMI performed experimental work that demonstrated reversible operation of single cells under conditions that represented the average predicted environment and gas composition in a reversible system. A sketch of the cell design for a reversible cell is shown in Figure 4. This work included design modifications tailored for reversible cell operation, preliminary sealing technology to prevent gas mixing, and modified gas distribution manifolds.

The cell area specific resistance (ASR) was about 10% higher for reversible cell designs compared to state-of-the-art TMI SOFC designs but was acceptable for early development. The best cells were operated in steady state (non-cycling) conditions for up to 2000 hours. This work is being actively extended to include the full range of predicted operation conditions in cells and in small stacks.

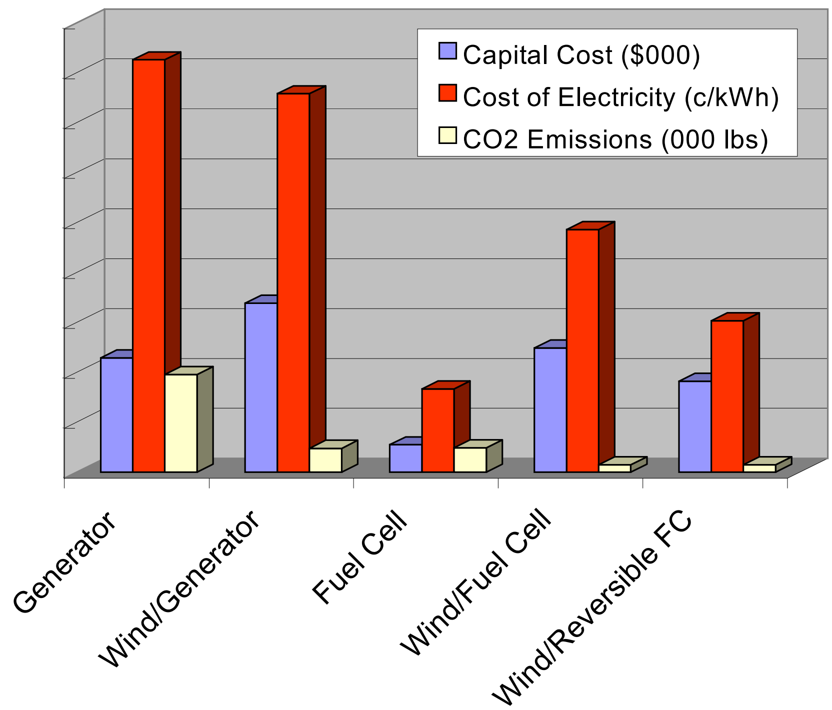


Figure 3. Costs and CO_2 Emission for Several Configurations

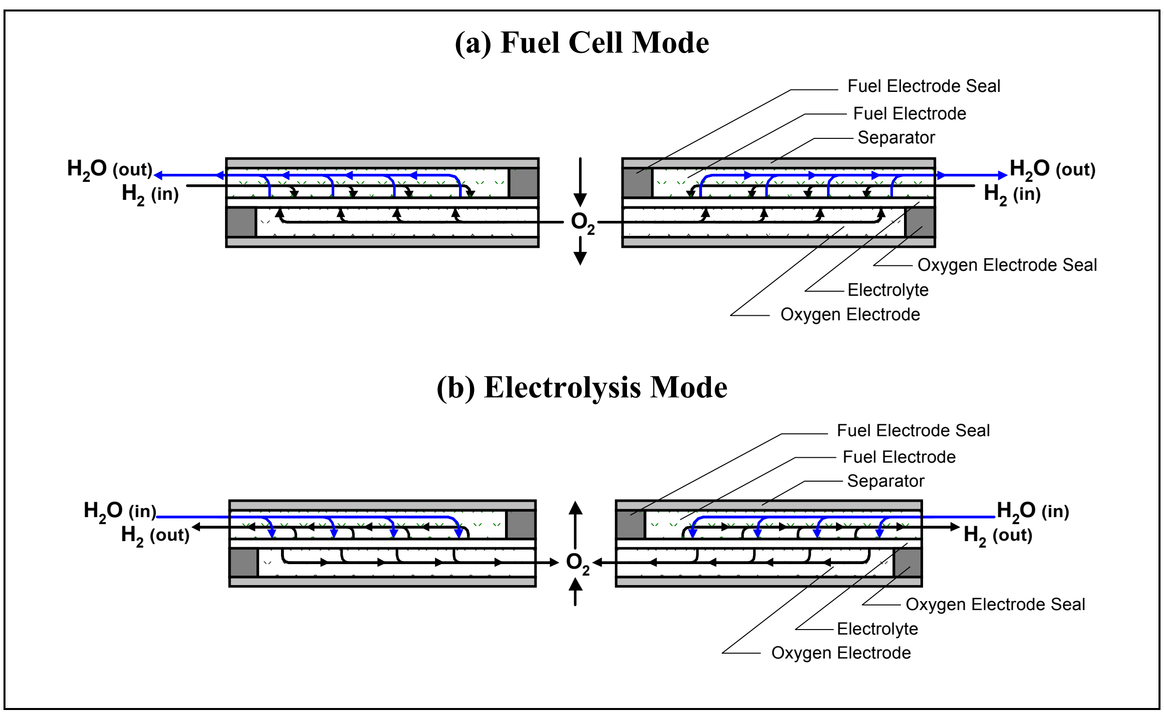


Figure 4. TMI Reversible Cell Flow Diagram

Conclusions and Recommendations

- The TMI reversible solid-oxide system is environmentally and economically attractive for renewable applications.

- TMI's high efficiency fuel cell systems has the potential for low costs and is a transitional technology en route to renewable-based systems.

- Additional experimentation is required to validate model assumptions.

On-going Work

This study is not complete. Three principal areas are being actively pursued: (1) reversible/high-efficiency small stack development and demonstration, (2) life and gas cycling experiments, and (3) updated cost and efficiency calculations.

Acknowledgements

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