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LOW COST REVERSIBLE FUEL CELL SYSTEM

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Abstract

TMI has studied a reversible solid-oxide fuel cell/electrolyzer system which would be capable of storing electrical energy generated from renewable sources at projected round-trip efficiencies over 80% and also of providing backup power generated from propane at lower heating value efficiencies over 60%. The systems would utilize a single set of stacks for all electrochemical functions together with a unique system design which stores both gases and thermal energy. The total system capital and operating costs are projected to be lower than comparable lead-acid battery plus backup generator systems.

Summary

1.1 Problem Statement

Grid-independent electric power systems based upon renewable power sources (chiefly solar, wind, and water) offer the promise of drastically reducing CO_2 emissions as well as offering unmatched siting flexibility and other advantages. However, the installed cost of complete, practical systems of this type is currently very high. Due to the intermittent and variable nature of renewable generation, such systems must have both a large energy storage capacity and backup generation for use when energy storage becomes depleted. The storage must be highly efficient in order to minimize renewable capacity needed. Currently, the only practical choice for these systems is deep-cycle lead acid batteries for storage plus an engine-generator for backup. Although these batteries can achieve high energy storage efficiencies near 80%, the battery/generator combination is quite expensive (first cost plus maintenance costs). Additionally, currently available generators are highly polluting, noisy, and have low fuel efficiencies (usually averaging below 30% lower heating value).

Based upon public literature, systems using Proton Exchange Membrane (PEM) fuel cell and electrolyzer technology are inherently incapable of achieving competitive energy storage efficiencies: known systems require electrolysis voltages which are far above their fuel cell voltages.

1.2 Proposed New Systems

Technology Management Inc. (TMI) has performed conceptual designs and simulations on a new low cost, reversible solid-oxide fuel cell/electrolyzer system which would use hydrogen and oxygen for energy storage and would also incorporate highly efficient backup power generation from propane and ambient air. A single solid oxide cells subassembly (which includes electrochemical stacks, heat exchange, fuel reformer, etc.) would be designed to operate in three (3) different modes:

1. Electrolysis mode (electrical energy to H_2 and O_2)

2. H_2/O_2 fuel cell mode (power from stored gases)

3. Propane/air fuel cell mode (power from propane and air)

The hydrogen and oxygen would be stored as gases at near-ambient temperature. Predicted energy storage efficiency (electrical energy out/electrical energy in) is near 80% (similar to lead acid batteries). Predicted propane efficiency is near 60% LHV, with negligible air pollutant emissions.

The system design utilizes multiple independent complete system modules for superior reliability. Thermal energy storage devices built into each module would provide a

delayed transfer of excess thermal energy generated as a product of fuel cell mode operation to supply the required thermal input during electrolysis mode. Projected initial and maintenance costs of these systems are significantly below existing options.

2. Introduction

TMI has studied possible system and subsystem options for small, grid-independent electric power generating systems. Three classes of options were investigated: those using available existing equipment, those using the planned TMI fuel cell systems for fossil fuels, and those using potential TMI systems having reversible fuel cells.

Grid-independent systems are viable markets because of one or more of the following reasons:

- Grid power is unavailable
- The cost of extending grid power to the site is too expensive
- Grid power has unacceptable reliability (too many power outages)
- Avoidance of unsightly and potentially dangerous overhead lines
- Grid power quality is unacceptable
- Traditional utilities cause considerable pollution
- Antipathy towards the local utility company
- Costly additional equipment is required by the utility for interconnection

A large number of existing grid-independent systems in this size range employ both a renewable power source (usually solar photovoltaic, wind turbine, or water turbine) and an engine-generator.

2.1 Example Requirements Summary

The example application used in this study is based upon a hypothetical remotely sited residence of 2500 square feet located near Boulder, Colorado. The power requirement is limited to 120 volts AC, 60 Hertz, single phase. Good power quality is 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 is also needed (system outages being very infrequent and brief). The residence is assumed to use propane fuel for all significant heating needs: space heating, cooking, hot water, and clothes drier. It has no air conditioning, but does use cooling fans (and possibly evaporative coolers) and many other 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) is 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. If 640 Watts is divided by the specified system peak capacity of 3000 Watts, the annual load factor of 21.3% is obtained. 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 thereby giving a cost of $11.86 per million BTU. Diesel fuel is assumed to cost $1.50 per gallon delivered with a LHV of 128,000 BTU/gal.

2.2 Technical Background Notes

Solid Oxide Fuel and Electrolysis Cells

Solid oxide fuel cells and electrolysis cells are electrochemical devices consisting of an impervious oxide-ion conducting solid oxide electrolyte, two porous electrodes (which perform charge transfer between electrons and oxygen ions), an electronically conductive impervious cell separator, and seals to confine the fuel and oxidizing gases to desired regions of the cell. In fuel cell mode, electric power is generated from a fuel gas (e.g. an H_2/H_2O mixture) and an oxidizing gas (normally air or oxygen). In typical electrolysis mode, steam is decomposed into hydrogen and oxygen, which are collected separately.

Design Philosophy

Energy balances for reversible systems must consider thermal, electrical, and chemical energies. Thermal energy can spontaneously flow only from higher to lower temperature. High efficiency reversible systems require that electrochemical and thermal processes are performed under conditions as close to equilibrium as practical. Prior experimental work at TMI has demonstrated electrochemical $H_2/O_2/H_2O$ cells operating with only small differences between their electrolysis and fuel cell voltages.

3. Proposed Reversible Solid-Oxide System

The proposed reversible system for the above example requirements would provide both energy storage (using H_2 and O_2) and backup generation from propane fuel. They would utilize two (2) identical reversible fuel cell/electrolyzer modules having the following preliminary specifications.

Table 1. Reversible Fuel Cell/Electrolyzer 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 module would contain the following components:

1. A triple-purpose solid-oxide stack, capable of operating in three (3) different modes:
    - Electrolysis mode for energy storage,
    - H_2/O_2 mode for recovering stored energy, and
    - Propane/air mode for supplemental generation
2. A hydrogen and oxygen gas storage system
3. A liquid water storage system
4. A multifunction power conditioning circuit
5. A small lead-acid battery for instantaneous load following
6. Required balance of system components, including compact heat exchangers, pump, blowers, valves, insulation, startup heater, control system, sensors, enclosure, etc.

Two modules would be connected as shown in Figure 1 below.

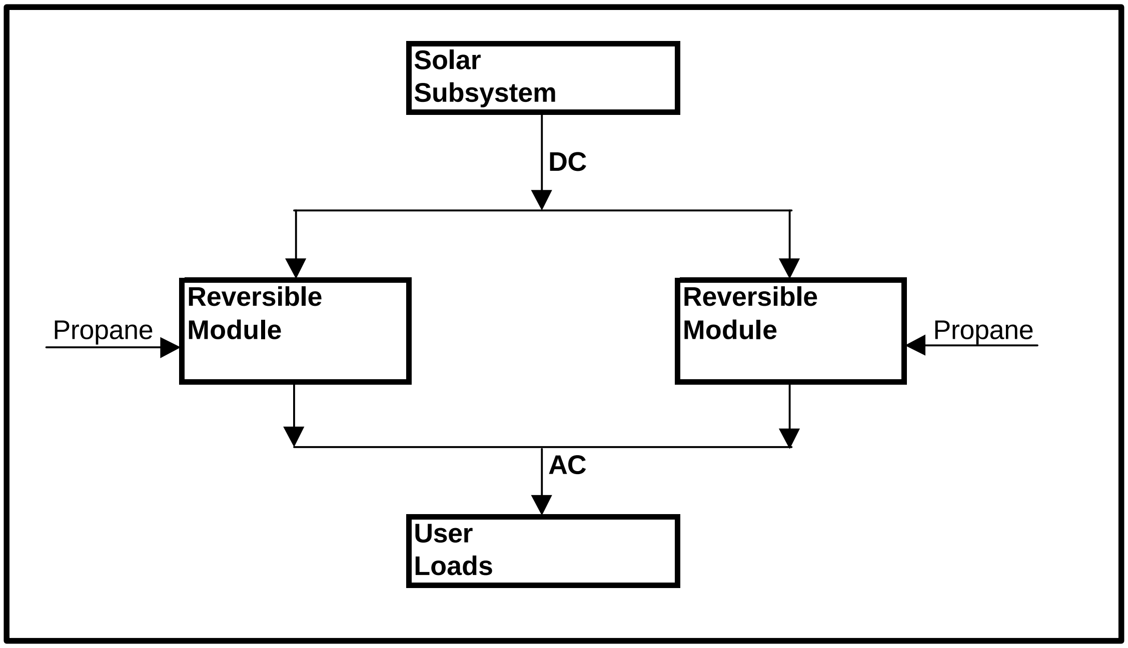


Figure 1: Connection of Two Reversible Modules

In the event of an outage of one module, the remaining module would supply the full user loads (at reduced efficiency).

4. Comparisons

The following table compares seven (7) cases analyzed in detail (using estimated 2009 selling prices for the new-technology systems). The installed costs in the table were computed using the specified system peak power requirement of 3.0 kW and are rounded to the nearest $100. The fuel cell systems in Cases D and E are the TMI high-efficiency type (these have no reversible storage capability). The fuel cell systems in Cases F and G are the previously described reversible type. Cases D through G each use two fuel cell modules. The percent solar power row refers to the share of user power requirements generated by solar. System comparisons using wind turbines would have different numbers, but similar relative positioning.

Table 2. Systems Comparison

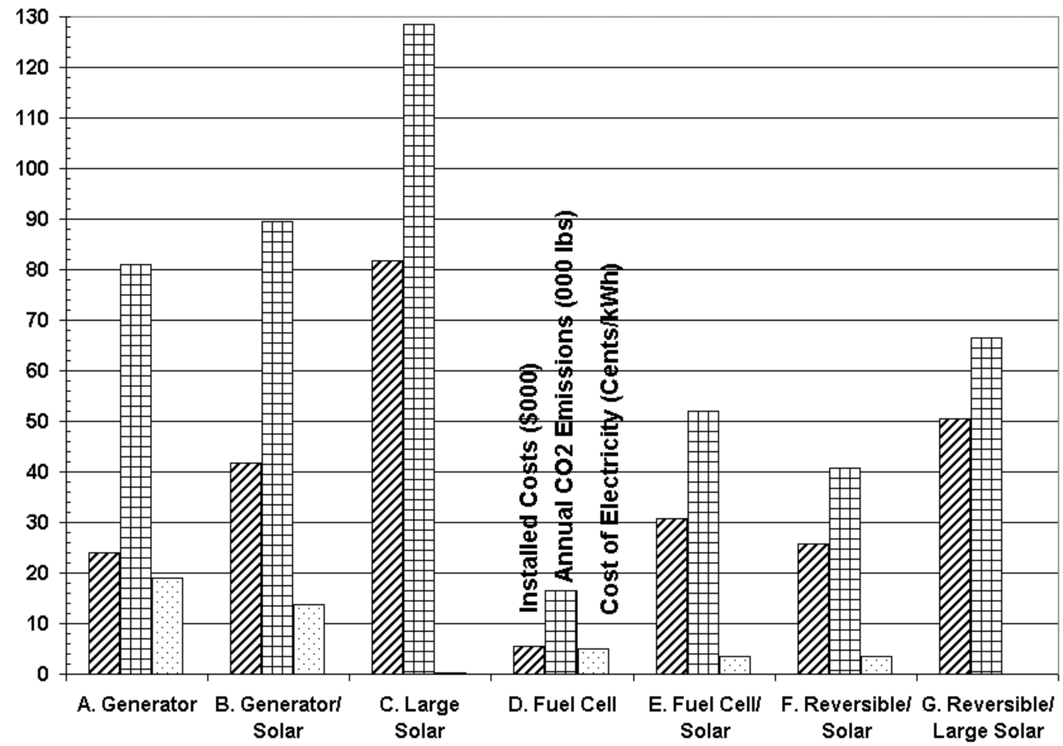
Case	A	B	C	D	E	F	G
Percent Solar Power	0	33	99	0	33	33	99
Primary Generation	propane engine	propane engine	none	propane fuel cell	propane fuel cell	propane fuel cell	none
Backup Generation	diesel engine	diesel engine	diesel engine	propane fuel cell	propane fuel cell	propane fuel cell	propane fuel cell
Primary Storage	lead-acid	lead-acid	lead-acid	lead-acid	lead-acid	hydrogen	hydrogen
Pollution	highest	high	low	~ 0	~ 0	~ 0	~ 0
Noise	highest	high	low	very low	very low	very low	very low
Installed Cost per kW	$ 8,000	13,900	27,300	1,800	10,300	8,600	16,800
Fuel, c/kWh	26.9	19.3	0.2	7.1	5.1	4.9	0.1
Maintenance, c/kWh	32.9	33.0	55.5	4.6	19.6	12.9	21.5
Cost of Electricity, c/kWh	81.1	89.5	128.6	16.6	52.1	40.7	66.6
Annual CO_2, tons	9.5	6.9	0.07	2.5	1.8	1.7	0.021

System D (TMI high efficiency fuel cell) has the lowest installed cost and the lowest cost of electricity. Systems F and G (using the TMI reversible fuel cell stacks) have the lowest installed cost for their respective solar capacities.

The reduction in CO_2 by using System G (reversible) instead of D (non-reversible) costs about $1000. per ton of CO_2 eliminated: a very high figure. By comparison, if System D were to be substituted for grid power made from coal, it would cost only about $100. per ton of CO_2 eliminated (in an application of this size).

Although the example application used in this report is based upon a good-sized residence, most of the considerations cited would also apply to smaller and larger systems having average power requirements anywhere from about 500 to at least 5000 Watts. The new technologies recommended would be applicable for both new installations and upgrades of existing systems. The following figure compares key values from Table 2.

Figure 2. Systems Comparison



5. Other Possibilities

The proposed new energy storage/fuel cell systems could also be used with wind or water power as the renewable source. The storage capacities for hydrogen, oxygen, and heat could be varied to match application needs.

Wherever natural gas is available, its typical cost is considerably lower than propane, leading to lower cost of electricity in fossil fuel mode.

6. Conclusions and Recommendations

- The TMI reversible solid-oxide system is environmentally and economically attractive for renewable applications having various renewable capacities

- TMI high efficiency fuel cell systems offer low predicted costs and could be a transitional technology en route to renewable-based systems

- A proposal for a follow-on development program is being prepared (see below)

Commercial introduction of the proposed systems could be possible as early as 2005.

A detailed report on the present study is now in preparation.

7. Proposal for Follow-On Development Program

The proposed high-efficiency fuel cell and reversible fuel cell/electrolyzer 1 kW modules and systems will require a technology development program to extend existing TMI technology and design concepts into a working hardware demonstration. The key questions about technical feasibility (proof of concept) can be answered by this program.

A draft proposal for the follow-on program will be available soon.

8. Acknowledgements

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