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**Fuel Cell and Reversible Fuel Cell Modules
for
Grid-Independent Electric Power Systems**

Final Report

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Prepared by:

Dr. Robert C. Ruhl
Vice President, Technology
(Principal Investigator)

Technology Management Inc.

9718 Lake Shore Blvd
Cleveland, Ohio 44108
(216) 541-1000
tmi@stratos.net

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1. Summary

Highly reliable, grid independent, electric power systems with average AC power outputs of 300 Watts and higher are often preferred for a variety of remote applications, including residences. Requirements for a selected example is given in Chapter 2. Propane is the assumed primary fuel available.

Available systems (Chapter 3) typically utilize engine-generators, lead-acid storage batteries, inverters, and frequently a renewable power source such as solar (photovoltaic panels) or wind (turbines). These systems have high installed costs and costs of electricity. Most produce considerable noise and air pollution and require significant maintenance.

Proposed systems using the high efficiency Technology Management Inc. (TMI) solid-oxide fuel cell (SOFC) described in Chapter 4, with or without renewable sources, offer the potential for lower installed cost and cost of electricity. In addition, they would be less polluting and significantly quieter. An advanced system (Chapter 5) utilizes reversible fuel cell modules for both energy storage and propane-fueled power generation. Comparisons of several grid-independent systems projected the following numbers for a selected remote residential application.

Table 1. Summary of Study Results

System Type	Installed Cost	Power Cost cents/kWh	Annual CO ₂ tons
Engine-Generator	\$22,900	83	9.8
Wind + Engine-Generator	\$33,900	76	2.4
TMI Fuel Cell	\$5,500	17	2.5
Wind + TMI Fuel Cell	\$24,900	49	0.7
Wind + TMI Reversible Fuel Cell	\$18,200	30	0.7

Predicted Costs for Example Grid-Independent Systems

The TMI Fuel Cell has the lowest Installed Cost and Power Cost.

The Wind + TMI Reversible Fuel Cell has the lowest cost of systems with very low CO₂.

2. Introduction

This report discusses several small system options for grid-independent electric power generating systems having average net AC power outputs of about 300 Watts and higher. Three classes of options are presented: those using available existing equipment (Chapter 3), those using the planned TMI fuel cell systems (Chapter 4), and those using potential TMI reversible fuel cell/electrolyzer systems (Chapter 5).

Grid-independent systems (i.e. having no connection to an electric utility power grid) may be employed for any of the following reasons:

- Grid power is unavailable
- The cost of extending grid power to the site is too expensive
- Avoidance of unsightly and potentially dangerous overhead lines
- Grid power has unacceptable reliability (too many power outages)
- Grid power has unacceptable quality
- Reduce utility-caused pollution
- Costly additional equipment is required by the utility for interconnection

It is believed that the majority of existing continuous duty, 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. Solar-based systems are described in References 5 and 6.

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 Colorado Springs, CO. The power requirement is limited to 120 volts AC, 60 Hertz, single phase. Good power quality is needed (true sine wave, 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 desired, with 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 dryer. It has no air conditioning, but does use cooling fans, an evaporative cooler, and a variety of small kitchen and household appliances. The maximum instantaneous peak AC demand (to start motors, etc.) is 3000 Watts and 4000 VA (35 Amps). The annual average AC power usage is assumed to be 15,300 Watt-hours/day, corresponding to an average level of 638 Watts. Figure 1 shows the assumed average load profile by hour of the day.

Figure 1 Assumed Average Hourly Load Profile

Power usage peaks in hour eight (7:00 to 8:00 a.m.) near breakfast time and again in hour 13 near lunch time. The large evening peak reaches an average hourly maximum of 1500 Watts during hour 19 (6:00 to 7:00 p.m).

The absence of air conditioning in this example reflects the reality that very few grid independent homes have air conditioning for reasons which will become apparent in the following chapter. 240-Volt power is not required since it is only required for large heating or air conditioning equipment, and rarely used with this type of system. The use of a single 120-Volt AC bus maximizes the flexibility of loads operation, since balancing of loads between the two legs of a 120/240 Volt system is not required.

Existing grid connected and grid independent homes vary greatly in their electric power consumption, usage patterns, and in other respects. The great majority of grid independent homes tend to practice greater energy conservation and thus use less electrical energy than do utility customers. The above example is believed to reflect a power usage which is above average among grid independent primary residences.

2.2 Wind Speed Assumptions

Values for wind speed for every three hours in Colorado Springs, CO for the months of January, April, July, and October 1999 were obtained (Ref. 9). The average values were as follows (note: the operating simulations in the following chapters do not use averages: these are included for information only).

Table 2. Wind Data for Colorado Springs, CO
(miles/hour)

Month	Minimum	Average	Maximum
January	0	10.2	37
April	0	12.9	45
July	0	10.0	32
October	0	8.5	26

2.3 Cost Assumptions

Costs cited in this report are in constant dollars and when appropriate are 20-year averages ("levelized"). The installed cost for each example system assumes professional installation by a licensed dealer/contractor, who would charge retail prices for all equipment and an estimated 25% times the sum of equipment prices for all installation labor, materials, and a margin.

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 of LHV. Battery maintenance costs are based upon the calculated battery life expected for the type of duty cycles used. Annual capital charges of 5% per annum are applied to all equipment except batteries, based on the assumed 20-year equipment life.

There are two components to the cash cost of electricity (expressed in cents per kilowatt-hour): fuel cost and maintenance cost. Maintenance cost includes preventive maintenance, hardware replacements, and breakdown repairs. The total cost of electricity is the sum of cash cost and capital charge. Although most of the cost of electricity values cited are considerably higher than for utility grid power, this comparison is only partially relevant for the reasons cited in the bulleted list at the start of this chapter.

The installed costs for the example systems in this report are based on the use of premium quality, new equipment and professional installation. Savings might be achieved through the use of lower quality and/or used equipment and by do-it-yourself installation. However, the relative ranking for the different cases should not change if consistent assumptions are used. Many system owners have found that initial cost-cutting steps have resulted in higher costs later on and sometimes safety problems, since several different types of possible hazards exist (electrical, flammable gas, and other).

2.4 Technical Background Notes

2.4.1 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 (usually hydrogen or a hydrogen-

containing gas mixture) and an oxidizing gas (air or oxygen). In electrolysis mode, steam is decomposed into hydrogen and oxygen which are collected separately.

2.4.2 Electrochemical Systems Design Philosophy

Energy balances for systems containing electrochemical cells must consider thermal, electrical, and chemical energies (i.e. the First Law of Thermodynamics). Thermal energy can spontaneously flow only from higher to lower temperature (i.e. the Second Law of Thermodynamics).

Very high efficiency electrochemical energy conversion or storage systems require that both electrochemical and thermal processes are performed under conditions as close to equilibrium as practical (i.e. electrochemical cells operate with low total polarization voltages and heat exchangers operate with small approach temperatures). Prior experimental work at TMI has demonstrated reversible solid oxide electrochemical $H_2/O_2/H_2O$ cells operating with only small differences between their electrolysis and fuel cell voltages (ref. 10).

3. Systems Using Existing Technologies

A number of different electric power generation system configurations are commercially available today which meet all requirements of the Chapter 2 example. Two example systems were selected and analyzed:

System A – Engine-generator only

System B – Wind turbine plus engine-generator

3.1 System A: Engine-Generator System

Table 3. shows the associated capital cost for the configuration shown in Figure 2.

Figure 2. System A: Engine-Generator

Table 3. System A Installed Cost

Item	Description	Brand	Model	Quantity	Each	Total
1	Deep Cycle Lead-Acid Batteries	Concorde	PVX12105	12	217	2,604
2	Battery Enclosure	SunWize	1545	1	798	798
3	Battery Accessories					200
4	Propane Generator Package	Generac	15-610	1	8,050	8,050
5	Diesel Backup Generator	Northern Pro	161454	1	2,580	2,580
6	Inverter/Battery Charger	Trace	SW4048	1	3,495	3,495
7	Power and Control Accessories					600
8	Total Installation Costs			25%		4,582
Total Installed Costs						\$22,909

All power requirements supplied by batteries are delivered with a considerably lower source-to-load net efficiency than power flows on a path NOT using the storage function. Lower efficiency results from the energy storage efficiency of the batteries themselves (typically about 80%, depending upon currents and other factors) as well as the added power conditioning losses when storage is employed.

Calculations performed on System A gave the following results.

Table 4. System A Cost of Electricity

	Ann Rate	Per Year	Per Month	Cents/kWh
Propane Generator Maintenance	12.5%	\$1,006	\$84	18.0
Batteries Maintenance	30.3%	790	\$66	14.1
Other Maintenance	2.0%	245	\$20	4.4
Subtotal Maintenance		\$2,041	\$170	36.5
Propane Fuel		\$1,557	\$130	27.9
Total Cash Costs		\$3,598	\$300	64.4
Capital Charge	5.0%	1,015	\$85	18.2
Total Cost of Electricity		\$4,614	\$384	82.6

The primary generator is operated for five hours per day at high-load times (split between morning and evening periods), supplying the loads and also recharging the batteries, at an average efficiency of 22% (AC/LHV). During the remainder of the day, batteries furnish energy to the loads. The backup generator is used only during outages (including planned maintenance periods) of the primary generator.

3.2 System B: Wind/Generator Example

Another grid independent system uses a combination of a wind turbine and engine-generators, as shown below.

Figure 3. System B: Wind/Generator

A projected 71% of the annual energy needs are generated by a nominal 3 kW wind turbine. This power is supplemented by the primary engine generator, which is operated daily as needed. The batteries provide sizeable energy storage, storing and delivering power as needed (including

surge power for starting motors, etc.). The power conditioning system performs all required power conversion, control, and protective functions.

Components of this system are further described below.

3.2.1 Wind Turbine Subsystem

A World Power model Whisper 3000 wind turbine/generator is used as an example. This unit has an integral power converter delivering 48 volts DC nominal with 3000 Watts nominal capacity. It uses two blades sweeping a 14.8 foot diameter circle. The power curve for this unit is shown in Figure 4:

Figure 4. Whisper 3000 Power Curve

The subsystem also includes a 70-foot tall tower with eight guys, cabling, and accessory items.

3.2.2 Batteries Subsystem

A total of 16 sealed deep cycle lead acid batteries are used, each rated at 105 Amp-hr and 12 Volts. The batteries are connected in an array of four in series by four in parallel to achieve an array rating of 420 Amp-hr at 48 Volts nominal (20.16 kWh nominal). The subsystem includes an outdoor battery enclosure, cables, temperature sensor, and safety features.

3.2.3 Engine-Generator Subsystem (same as in system A)

The main engine-generator is a heavy duty 7.0 kW propane-powered model, with automatic starting, safety systems, controls, air filter, and outdoor sound-attenuating enclosure. Also included is a diesel-powered backup generator with manual starting for use during main generator outages. The subsystem also includes switchgear, cabling, fuel supply hardware, and sensors.

3.2.4 Power Conditioning Subsystem

This subsystem includes the following components:

1. A 4000 VA sine-wave inverter to produce 120 VAC, 60 Hz output power from a 48-Volt nominal DC battery bus
2. A 60-Amp, 48-Volt nominal battery charger to recharge the batteries from either generator
3. User controls and displays
4. Automatic controls
5. Protective safety components
6. Interconnecting cables
7. Interface for personal-computer data transfer
8. Wall-mounted cabinet

3.2.5 Installation

These systems are technically complex, expensive, and contain various types of potential safety hazards. They normally require a qualified, experienced, and licensed contractor to perform customized electrical engineering work and install the complete system in accordance with all applicable safety codes.

The system has an estimated turnkey installed cost of \$33,903, as detailed in Table 5. This cost does not include the cost of the household propane tank or the household power wiring (with circuit breaker panel).

Table 5. System B Installed Cost

Item	Description	Brand	Model	Quantity	Each	Total
1	Wind Turbine	World Power	Whisper 3000	1	6,290	\$6,290
2	Tower for Above	World Power	GP3-20K8	1	1,260	\$1,260
3	Wind System Accessories			1	600	600
4	Deep Cycle Lead-Acid Batteries	Concorde	PVX12105	16	217	3,472
5	Battery Enclosure	SunWize	1545	1	798	798
6	Battery Accessories			8%		278
7	Propane Generator Package	Generac	15-610	1	8,050	8,050
8	Diesel Backup Generator	Northern Pro	161454	1	2,580	2,580
9	Inverter/Battery Charger	Trace	SW4048	1	3,495	3,495
10	Power and Control Accessories			1	300	300
11	Total Installation Costs			25%		6,781
Total Installed Costs						\$33,903

3.2.6 System B Operation and Cost of Electricity

The Figure 4 curve, together with wind data for every three hours of the four months (assumed to represent the full year) was used to compute the wind power production profiles. The generator is used for up to five hours per day (during periods of little or no wind). The batteries are used to store both wind and generator power in excess of immediate needs. An average of 71% of the annual power needs are supplied by wind, either directly or via batteries. Table 6 gives the calculated cost of electricity.

Table 6. System B Cost of Electricity

	Ann Rate	Per Year	Per Month	Cents/kWh
Propane Generator Maintenance	9.0%	\$ 725	\$ 60	13.0
Batteries Maintenance	30.0%	\$ 1,042	\$ 87	18.6
Other Maintenance	2.5%	\$ 560	\$ 47	10.0
Subtotal Maintenance		\$ 2,326	\$ 194	41.6
Propane Fuel		\$ 388	\$ 32	6.9
Total Cash Costs		\$ 2,713	\$ 226	48.6
Capital Charge	5.0%	\$ 1,522	\$ 127	27.2
Total Cost of Electricity		\$ 4,235	\$ 353	75.8

3.3 Storage Battery Subsystems Discussion

Deep cycle lead-acid batteries are currently the most cost-effective energy storage means for the example systems in this chapter, with no alternatives approaching them in cost. Several different types of such batteries are commercially available, each with various cell counts (voltages) and amp-hour capacities. For applications of this nature, the preferred type is "sealed" (actually valve-regulated) and may use a gel electrolyte. The preferred size is expected to be light enough for one person to lift. A 12 Volt, 105 Amp-hour example is the Concorde Model PVX12105, which weighs 68 pounds and is 12.91 x 6.75 x 9.25 inches. Multiples of four of these batteries may be connected into a single bank of 48 Volts nominal, which is the preferred voltage for many existing types of power conditioning units. Since battery capacity decreases in cold temperatures and life decreases in hot temperatures, maintaining their temperatures close to room temperature year around is desirable. The estimated costs for installation include provisions for simple temperature control and safety ventilation.

The useful life of deep cycle lead-acid batteries depends primarily on the type of batteries used, temperatures of use, and the details of charging and discharging. Under unfavorable conditions, battery life can be less than one year. Under very good conditions, over ten years of life can be achieved. In general, limiting the operating depth of discharge has a significant impact on battery life, with under 50% recommended except for rare occasions. The reported data on battery life versus depth of discharge from Concorde were used for the battery replacement cost calculations included herein. The calculated useful battery life in a system having minimized cost of electricity was typically 3 to 5 years.

The energy storage efficiency of lead acid batteries depends upon the currents used for charging and discharging, declining with higher currents. Efficiency also depends upon the state of charge,

declining as batteries approach a fully-charged condition (Ref. 7). In this type of application, energy storage efficiencies of about 80% are believed to be attainable.

3.4 Conventional Technology Systems Discussion

Many variants of the above two example systems are possible. Instead of (or in addition to) a wind turbine, some existing systems use solar photovoltaic panels or water turbines as a renewable power source. All renewable power sources have the attraction of zero fuel cost, zero pollution, and (usually) low or no noise. However, these systems have the disadvantages of producing intermittent, variable outputs and of being quite expensive per unit of capacity. Turbines require more maintenance and produce more noise than solar panels, but lead to lower costs when located at favorable wind sites.

Other variants may use different generator fuels (natural gas, diesel, or gasoline). Where available, natural gas typically is significantly lower in cost than delivered propane. Gasoline is much more hazardous than the other fuels, especially when large quantities must be stored, and thus diesel was selected as the backup fuel of choice for this study.

Some existing systems have both AC and DC final power outputs. Some have dual 120/240 Volts AC output. International systems are available with other voltages and 50 Hertz. A larger-capacity battery charger can be purchased for more rapid recharging of the batteries from the generator. More rapid battery charging would reduce the required daily duration of generator operation, but would slightly lower the overall net system efficiency (the slight improvement in generator efficiency is more than offset by the greater daily use of battery power and increased charging losses at higher charging currents).

Systems using currently available technology for the example application have a high installed cost, poor fuel efficiency, and high annual maintenance costs. The systems are noisy and polluting (especially when the generators are running) and many have marginal reliability. In spite of these limitations, however, over 100,000 grid independent homes are estimated to exist in the U.S. (Refs. 3, 4). If new electric power systems having superior performance and/or cost were to become available, the potential number of new users is expected to increase.

In the future, the costs for the equipment types cited above are expected to decline moderately as technology improves and sales volumes increase. The future price of fuels will fluctuate and probably trend upwards. The following chapters will present possible systems using proposed new technologies, with superior cost and emission values to either type of system described in this chapter.

4. Systems Using Regular Fuel Cells

The possibility of replacing engine-generators in grid independent systems with fuel cell systems has been considered by many individuals and companies, including TMI. The appeal of fuel cell systems is in the potential to simultaneously achieve the following^[1], when compared with engine-generators:

- improved fuel efficiency and hence lower CO₂ emissions
- virtual elimination of pollution
- much lower noise
- improved reliability
- lower installed and maintenance costs

The preferred fuel (for fuel cell systems) is the same fuel being used at the site for space heating and/or cooking such as propane (in this report), natural gas, or kerosene. All of these are relatively clean hydrocarbon fuels and are much less expensive (per unit of energy content) than other types of clean fuels (alcohols, hydrogen, etc.).

In this report, the term "Regular Fuel Cells" refers to planned TMI fuel cell systems operating exclusively on fossil fuel such as propane to produce electric power. In Chapter 5, another possibility, "Reversible Fuel Cells," is discussed. Two regular fuel cell systems have been evaluated in some detail and are discussed below: a fuel cell only system ("System C") and a wind turbine/fuel cell system ("System D"). System C is the fuel cell counterpart to System A in Chapter 3 and System D is the fuel cell counterpart to System B.

Both Systems C and D assume four (propane) fuel cell modules with the provisional TMI model number 10G4 (see Table 6). This module incorporates an advanced sine-wave inverter and maintains very high efficiency over a broad range of power output levels, including low power conditions. It is capable of instantaneous load following with good voltage regulation. Any number of these modules could be connected in parallel for increased output and further redundancy.

Considerable simulation and engineering calculations support the proposed fuel cell modules, including detailed material and energy balances and electrochemical calculations. The modules would be designed for safe indoor installation, with approximate dimensions of 12 inches square by 72 inches tall and an estimated weight of 65 pounds. They would incorporate TMI's sulfur-tolerant fuel reformer and solid-oxide fuel cell stacks, which are compatible with ordinary dealer propanes. The exhaust would be extremely clean, with expected NO_x levels below 1 ppm, and no emissions of particulates, organics, or carbon monoxide. They would have "hot swap" capability, whereby a module can be exchanged while the remaining modules continue to operate normally.

[1] once commercially available and produced in quantity

Table 7. Preliminary Specifications of Fuel Cell Module

TMI Model 10G4
(continuous ratings)

Parameter	Value	Units
Maximum AC Output Power	1000	Watts
Maximum Apparent Power	1700	VA
Maximum AC Current	15	Amps
Output AC Voltage (60 Hz)	120	Volts
Typical Net Propane Efficiency	60%	LHV
Noise @ 1 meter	< 40	dbA

4.1 System C: Fuel Cell Only System

This system consists of four model 10G4 fuel cell modules connected in parallel and a mounting rack with costs (using 2009 cost estimates) shown in Table 8.

Table 8. System C Installed Cost

Item	Description	Brand	Model	Quantity	Each	Total
1	Fuel Cell Module 1 kW	TMI	10G4	4	1,000	4,000
2	Mounting Rack	TMI	R4	1	400	400
3	Installation Costs			25%		1,100
Total Installed Costs						\$5,500

All fuel cell modules normally operate continuously, automatically sharing the user load equally. In the event of a module outage, the remaining modules remain capable of supplying the worst-case instantaneous demand of 3000 Watts and 4000 VA. The results of operating cost calculations are as follows.

Table 9. System C Cost of Electricity

	Ann Rate	Per Year	Per Month	Cents/kWh
Fuel Cell Modules Maintenance	6.0%	\$240	\$20	4.3
Other Maintenance	2.0%	\$30	\$3	0.5
Subtotal Maintenance		\$270	\$23	4.8
Propane Fuel		\$390	\$32	7.0
Total Cash Costs		\$660	\$55	11.8
Capital Charge	5.0%	275	\$23	4.9
Total Cost of Electricity		\$935	\$78	16.7

Both capital and operating costs of the fuel cell only system (System C) are low enough to make ordinary air conditioning practical for this application. If one additional module were added, one large or two small window air conditioners could be powered in addition to other household loads. If two fuel cell modules were added, a central air conditioning system could be powered. The cash costs per kWh shown in Table 8 are comparable to utility power charges in many parts of the U.S.

4.2 System D: Wind/Fuel Cell System

A wind turbine plus fuel cell system configuration is shown below.

Figure 5. System D: Wind/Fuel Cell

A wind/fuel cell system could be an upgrade of an existing wind turbine/engine-generator system or a completely new installation. Fewer batteries are needed than the wind/generator (system B) example, since the fuel cells operate continuously compared to five hours per day (maximum) for the engine-generator. The wind/fuel cell example has an estimated installed cost as follows.

Table 10. System D Installed Cost

Item	Description	Brand	Model	Quantity	Each	Total
1	Wind Turbine	World Power	Whisper 3000	1	6,290	\$6,290
2	Tower for Above	World Power	GP3-20K8	1	1,260	\$1,260
3	Wind System Accessories			1	600	600
4	Deep Cycle Lead-Acid Batteries	Concorde	PVX12105	12	217	2,604
5	Battery Enclosure	SunWize	1545	1	798	798
6	Battery Accessories			8%		208
7	Fuel Cell Module 1 kW	TMI	10G4	4	1,000	4,000
8	Mounting Rack	TMI	R4	1	400	400
9	Inverter/Battery Charger	Trace	SW4048	1	3,495	3,495
10	Power and Control Accessories			1	300	300
11	Total Installation Costs			25%		4,989
Total Installed Costs						\$24,944

4.2.1 System D Operation and Cost of Electricity

Operation would be fully automatic. In the event of a fuel cell module outage, the remaining modules would supply all load requirements. Table 11 shows operating costs for System D.

Table 11. System D Cost of Electricity

	Ann Rate	Per Year	Per Month	Cents/kWh
Fuel Cell Modules Maintenance	6.0%	\$ 240	\$ 20	4.3
Batteries Maintenance	30.0%	\$ 781	\$ 65	14.0
Other Maintenance	2.5%	\$ 459	\$ 38	8.2
Subtotal Maintenance		\$ 1,480	\$ 123	26.5
Propane Fuel		\$ 117	\$ 10	2.1
Total Cash Costs		\$ 1,597	\$ 133	28.6
Capital Charge	5.0%	\$ 1,117	\$ 93	20.0
Total Cost of Electricity		\$ 2,714	\$ 226	48.6

4.3 Fuel Cell Systems Discussion

The two systems described in this chapter have major cost and emission advantages compared to the conventional counterparts from Chapter 3 (all the systems in this report are compared in Chapter 6). Fuel cell systems are intrinsically much quieter than engine-generators and will consume much less fossil fuel due to their high efficiencies. The addition of a wind turbine and batteries to a fuel cell system is quite costly, but lowers both fuel costs and CO₂ emissions. Upgrading existing wind turbine systems with fuel cell modules is an especially attractive option, since many of the large costs are already "sunk".

5. Systems Using Reversible Fuel Cells

5.1 Reversible Fuel Cell Modules

TMI has conceived a preliminary design for a reversible fuel cell module capable of functioning as both a regular propane/air fuel cell module and as an energy storage battery using hydrogen and water. Its three operating modes would be used as follows:

1. Energy Storage (Electrolysis) Mode

When wind turbine output exceeds the electrical load demand, excess power is used to electrolyze (decompose) water into hydrogen (stored as a pressurized gas at room temperature) and oxygen (which would be vented).

2. Hydrogen Mode

When the load demand exceeds wind turbine output, stored hydrogen is used together with ambient air to generate power via fuel cell operation.

3. Propane Mode

When the load demand exceeds wind turbine output and the stored hydrogen supply is depleted, propane is used together with ambient air to generate power via fuel cell operation.

Specifications for the reversible fuel cell module are as follows.

Table 12. Preliminary Specifications of Reversible Fuel Cell Module
TMI Model 10R4

Parameter	Value	Units
Practical Storage Capacity	3000	Watt-hours
Input Voltage Range	45-70	DC Volts
Maximum Charging Input	1000	DC Watts
Output AC Voltage	120	Volts
Maximum AC Output Power	1000	Watts
Maximum Apparent Power	1700	VA
Maximum AC Current	15	Amps
Typical Net Propane Efficiency	60%	LHV
Typical Energy Storage Efficiency	73%	Wh/Wh

The reversible module design concept is based on the (model 10G4) propane/air module, with its features for high efficiency operation on propane. In addition to the 10G4 module, the reversible module would include hydrogen gas and liquid water storage tanks, fuel mix recycle blower, power input controller/converter, hot thermal storage mass, solenoid valves, and more complex controls. High energy storage efficiency (approaching that of lead acid batteries) would result from the use of excess high temperature thermal energy released during fuel cell modes to supply some of the energy requirements during electrolysis and from a number of other design features. Hydrogen gas storage would occur in outdoor tanks at medium pressures, with built-in safety devices.

The proposed design would be capable of both very rapid load following performance and operating mode transitions without output voltage difficulties. Preliminary material and energy balances and electrochemical calculations have been performed for all three modes of operation of these modules.

5.2 System E: Wind/Reversible Fuel Cell

The reversible fuel cell modules described above would be combined with a wind turbine subsystem as follows.

Figure 6. System E: Wind/Reversible Fuel Cell

System E uses the same wind subsystem as Systems B and D. The installed costs and cost of electricity for System E are given in Tables 13 and 14, using 2009 estimated prices.

Table 13. System E Installed Cost

Item	Description	Brand	Model	Quantity	Each	Total
1	Wind Turbine	World Power	Whisper 3000	1	6,290	\$6,290
2	Tower for Above	World Power	GP3-20K8	1	1,260	\$1,260
3	Wind System Accessories			1	600	600
4	Reversible Fuel Cell Module 1 kW	TMI	10R4	4	1,500	6,000
5	Mounting Rack	TMI	S4	1	600	400
6	Total Installation Costs			25%		3,638
Total Installed Costs						\$18,188

Table 14. System E Cost of Electricity

	Ann Rate	Per Year	Per Month	Cents/kWh
Reversible Modules Maintenance	6.0%	\$ 360	\$ 30	6.4
Other Maintenance	2.5%	\$ 305	\$ 25	5.5
Subtotal Maintenance		\$ 665	\$ 55	11.9
Propane Fuel		\$ 118	\$ 10	2.1
Total Cash Costs		\$ 783	\$ 65	14.0
Capital Charge	5.0%	\$ 909	\$ 76	16.3
Total Cost of Electricity		\$ 1,692	\$ 141	30.3

6. Discussion, Conclusions, and Recommendations

6.1 Comparison of Cases Studied

Table 15 compares five cases analyzed in detail (using the estimated 2009 selling prices for the new-technology systems). The Unit Costs in Table 15 were computed using the specified peak power requirement of 3.0 kW and rounded to the nearest \$100. Other units costs may be computed if desired using various other divisors, such as the peak kVA requirement of 4.0, etc. The "Percent Wind Power" values are the share of user annual energy requirements supplied (either immediately or via storage) by wind.

Table 15. Systems Comparison

	A	B	C	D	E
Percent Wind Power	0	71	0	71	71
Primary Fuel-Based Generation	propane engine	Propane Engine	propane fuel cell	propane fuel cell	propane fuel cell
Backup Fuel-Based Generation	diesel engine	Diesel engine	propane fuel cell	propane fuel cell	propane fuel cell
Energy Storage	lead-acid	lead-acid	none	lead-acid	hydrogen
Pollution	highest	Medium	~ 0	~ 0	~ 0
Noise	highest	High	very low	medium	medium
Total Installed Cost	\$ 22,900	\$ 33,900	\$ 5,500	\$ 24,900	\$ 18,200
Unit Cost per kW	\$ 7,600	\$ 11,300	\$ 1,800	\$ 8,300	\$ 6,100
Fuel per kWh	\$ 0.279	\$ 0.069	\$ 0.070	\$ 0.021	\$ 0.021
Maintenance per kWh	\$ 0.365	\$ 0.416	\$ 0.048	\$ 0.265	\$ 0.119
Total Cash per kWh	\$ 0.644	\$ 0.486	\$ 0.118	\$ 0.286	\$ 0.140
Cost of Electricity per kWh	\$ 0.826	\$ 0.758	\$ 0.167	\$ 0.486	\$ 0.303
Annual CO₂, tons	9.8	2.4	2.5	0.7	0.7

System C has the lowest installed cost and the lowest cost of electricity. Systems D and E have the lowest CO₂ emissions. System E has the lowest installed cost of the example renewable systems. Figure 7 compares key values from Table 15.

Figure 7. Systems Comparison

A. Generator B. Wind/Gen C. Fuel Cell D. Wind/FC E. Wind/Rev. FC

6.2 Other Wind Capacities

The installed wind turbine capacity may be varied from the 3 kW nominal rating in Cases B, D, and E. As wind capacity is decreased, the installed cost and the cost of electricity decrease while the annual fuel cost and CO₂ emissions increase. The differences between Cases A and B and between C and D (or E) may be used to perform approximate interpolation or extrapolation for other wind capacities. However, at very large wind capacities, the law of diminishing returns will drive installed cost and cost of electricity even higher (since the final capacity increment will be utilized only occasionally).

6.3 Natural Gas and Other Fuels

Propane was used above as the base case example fuel due to its nearly universal availability throughout the U.S. However, propane is relatively expensive (in the example used, \$1.00 per gallon delivered or \$11.86 per million BTU of lower heating value). Also, propane is somewhat more hazardous than natural gas or kerosene.

Pipeline natural gas is available in many locales, particularly in urban and suburban regions. The retail price of natural gas is generally much lower than propane, with an example being \$4.00 per thousand cubic feet or \$4.35 per million BTU of lower heating value. Models of engine-generators are now available for natural gas and the proposed new fuel cell system models are

planned to have natural gas model variants. To a first approximation, both the installed costs and the fuel consumption (based upon lower heating value) of natural gas systems will be the same as for propane systems. Thus in the fuel cell only system (System C) the fuel cost will drop from 7.0 cents/kWh using propane to 2.6 cents/kWh using natural gas.

Kerosene is already used for space heating in some residences and is widely available. If market demand warrants, TMI expects to offer fuel cell models designed to operate on kerosene. Kerosene is typically priced between propane and natural gas per million BTU, and offers considerably higher energy content per gallon than propane and lower fire hazards than either propane or natural gas. As with the natural gas models, the installed costs and efficiencies of kerosene-fueled versions of the example systems will be very similar to the propane cases. Some sites requiring propane for other uses may prefer the convenience of a single fuel in spite of the higher unit cost of propane.

6.4 Grid Interconnection and Power Export

Several possible reasons for having no grid connection are listed in Chapter 2. Although it is believed that most owners of the types of systems described in this report will not be connected to the utility power grid, some owners may prefer to have a grid connection for the following reasons:

1. Revenue from the sale of surplus power to the utility
2. Supplement an undersized system
3. Redundancy
4. Reduce utility pollution

TMI plans to offer grid-interface packages for its fuel cell systems. These will include automatic and manual disconnect/reconnect functions, synchronization, safety systems, and optional instrumentation. The utility company will furnish single or bi-directional watt-hour meters, as appropriate. The incremental installed cost for grid interconnection will vary depending upon utility requirements and proximity.

Although utility power purchase rates differ considerably in various locales (some locations in California reportedly pay about 4 cents/kWh), the incremental or marginal cost of renewable power generation is virtually zero. For natural gas systems, the *incremental* cost of power generation will typically be slightly lower than the *average* cost of 2.6 cents/kWh (cited in section 6.3) and will thus make power sales using natural gas slightly profitable in some locales. Due to the considerably higher cost of propane fuel, it will seldom be cost-effective to generate extra power for sale using propane.

6.5 Cogeneration (Combined Heat and Power)

System C (which has the highest surplus heat production of all the advanced systems, C through E) has an average surplus heat production of about 1580 BTU/hour. A good add-on heat recovery system might recover 80% of this energy or about 1250 BTU/hour. If this energy were used to heat domestic hot water from a well temperature of 50°F to 120°F, a total of about 51 gallons of water per 24 hours could be heated. The average energy efficiency of the combined

system using heat recovery could increase from 58% to over 90% on a lower heating value basis (provided all the hot water is needed).

If this hot water is normally heated by a propane water heater operating at 60% LHV efficiency, the annual fuel savings using add-on heat recovery is \$216. The incremental installed cost of add-on heat recovery units for twin fuel cell modules is estimated to be roughly \$1000., giving a payback period for the heat recovery add-on of 4.6 years. The avoided additional CO₂ emissions using heat recovery would be about 1.4 tons per year.

6.6 Other Fuel Cell Module Sizes

Design and manufacture of fuel cell modules smaller or larger than the 1 kW examples used herein are possible. TMI has previously performed module manufacturing cost projections for sizes larger and smaller than 1 kW. As expected, the forecast costs per kilowatt decline as module kW capacity increases.

Larger systems are expected to benefit from the use of the expected 2 and 3 kW fuel cell modules with their lower installed cost per kW. Any quantity of modules may be ganged for larger systems.

6.7 Other Hydrogen Storage Capacities

The incremental cost of additional hydrogen gas storage capacity is relatively low compared with the cost of a 10R4 module. However, the limited amount of practical high-temperature thermal storage for this module will cause a moderate drop in storage efficiency for larger storage capacities.

6.8 Future Cost Possibilities

The projected installed costs for fuel cell modules and systems cited above for about 2009 are expected to decline with increasing annual production levels. It is also probable that increased use of renewable and other distributed generation technologies will lead to future reductions in their costs as well. In summary, all of the types of systems cited in this report have potential for ongoing declines in installed and operating costs. These declines may have little impact on their rankings in comparison with one another, but could have a large impact when the independent systems are compared with grid power.

Future fuel prices will also affect the costs of both distributed and utility power. In general, higher fuel prices will improve the operating cost advantages of highly efficient and renewable technologies.

6.9 Systems using Solar Photovoltaic Power

Photovoltaic analogs (Refs 5, 6, and 8) of Systems B, D, and E were studied, using a 2100 Peak Watt solar array. The example site was Boulder, CO and used solar data from Ref. 1.

Table 16. Wind vs Solar Systems

System	Solar Installed	Wind Installed	Solar Cost/kWh	Wind Cost/kWh
B: Generator-Pb Acid	\$42,900.	\$33,900.	\$0.889	\$0.758
D: Fuel Cell-Pb Acid	\$34,000.	\$24,900.	\$0.522	\$0.486
E: Fuel Cell-Hydrogen	\$27,900.	\$18,200.	\$0.405	\$0.303

Estimated installed costs and cost of electricity are lower for the selected wind turbine system examples than for the solar system examples. The wind system examples also emit less CO₂ and consume less propane than the solar examples selected, since they generate a larger fraction of their power from renewables. The wind turbine is, however, noisy and requires a suitable site for installation. Many locations in the U.S. have lower wind speeds than does the example site. The cost rankings of the 5 types of systems given in Table 14 remain in the same order for wind systems as for solar systems.

6.10 Other Electrical Energy Storage Technologies

This report has analyzed two types of electrical energy storage technologies: deep cycle lead-acid batteries and proposed TMI reversible fuel cell systems. Numerous other electrical energy storage technologies have also been used or considered by TMI and others, including the following. Any storage technology exhibiting low storage (e.g. below about 70%) efficiency will require expensive additions to renewable generation capacity for comparable results.

6.10.1 PEM Electrolyzers and PEM Fuel Cells

A study of a system using PEM electrolyzer and PEM fuel cell subsystems was recently performed by the Desert Research Institute (Ref. 2). Its net energy storage efficiency was close to 30%.

6.10.2 TMI Systems using High Pressure Steam

TMI studied H₂/O₂/H₂O electrical energy storage systems for low earth orbital applications under NASA SBIR contracts during the 1990s. These systems were projected to be capable of achieving energy storage efficiencies above 85% for applications using 92-minute charge-discharge time cycles. However, these systems required very expensive advanced composite materials and thus would not be cost effective for this proposed application.

During this program, non-condensing high pressure H₂/O₂/H₂O systems using insulated steel tanks were considered. These systems showed possible energy storage efficiencies slightly over 80% under favorable conditions, but are not compatible with propane operation and have considerably higher technical and safety risks.

6.10.3 Other Types of Secondary Batteries

Although certain other types of secondary batteries are capable of 70% or higher energy storage efficiency, all cost more than deep cycle lead acid batteries and are less cost effective for this type of application (Ref. 7).

6.10.4 Other Methods for Gas Storage

Numerous other technologies have been used or considered for hydrogen storage and some for oxygen storage. Future engineering studies should evaluate alternatives (including metal hydride storage) to the proposed moderate pressure hydrogen storage with respect to costs, efficiencies, safety considerations, and response times.

6.10.5 Other Storage Technologies

Other electrical energy storage technologies include ultra-capacitors, flywheels, pumped fluids, and superconducting magnets.

6.11 Laboratory Measurements

6.11.1 Reversible Cells

A total of 10 reversible fuel cells were tested. The tests included seal leakage and cell electrochemical performance in both fuel cell and electrolysis modes (hydrogen/steam fuel mixtures and air oxidizer). Cell performance was measured versus a wide range of fuel mix compositions (% H₂O), current density, temperature, and time. The longest test was continued for over 2400 hours of continuous operation (still operating at this writing). Various cell fabrication methods and component dimensions were tested. Cell performance under various conditions was quantified by computing its Area Specific Resistance (ASR, in ohm-cm²) and by its cell voltage at about 200 mA/cm² current density. The best cell exhibited an aging rate (power loss at constant flow, compositions, and temperature) of 6.4% per 1000 hours, a moderate increase in ASR versus fuel mixture H₂O concentration, and electrolysis performance somewhat better than fuel cell performance (typical electrolysis ASR was about 80% of fuel cell ASR).

6.11.2 Lead Acid Batteries

The energy storage efficiency of a Concorde Model PVX-12105 deep cycle lead acid battery (absorbed glass mat separator type) was measured for simulated typical solar cycles (approximately 8 hours charge and 16 hours discharge) at 32% depth-of-discharge swing. The measured energy storage efficiency was 92.0% on a new battery at 23°C ambient temperature, which is considerably higher than the values of 70-75% reported in the literature (Ref. 7) for other styles of lead acid batteries. Estimates suggest that an energy storage efficiency near 80% would be expected for a Concorde battery when averaged over the life of the battery (and with operation at various temperatures and currents). This efficiency estimate was used for the simulations reported herein.

6.12 Development Program

Implementation of both the high efficiency propane/air modules and the reversible modules require a focused technology development program which adapts TMI's "mainstream" technology to the more demanding conditions. A proposal for this development program is being submitted with this report.

7. References

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