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Abstract

Technology Management, Inc. (TMI) of Cleveland, Ohio, has completed the project entitled “Small Scale SOFC Demonstration using Bio-based and Fossil Fuels.” Under this program, two 1-kW systems were engineered as technology demonstrators of an advanced technology that can operate on either traditional hydrocarbon fuels or renewable biofuels. The systems were demonstrated at Patterson's Fruit Farm of Chesterland, OH and were open to the public during the first quarter of 2012. As a result of the demonstration, TMI received quantitative feedback on operation of the systems as well as qualitative assessments from customers. Based on the test results, TMI believes that *> 30% net electrical efficiency at 1 kW on both traditional and renewable fuels with a reasonable entry price is obtainable*. The demonstration and analysis provide the confidence that a 1 kW entry-level system offers a viable value proposition, but additional modifications are warranted to reduce sound and increase reliability before full commercial acceptance.

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Executive Summary

Technology Management, Inc. (TMI) of Cleveland, Ohio, completed demonstration of two fuel-flexible 1-kilowatt scale high temperature solid oxide fuel cell (SOFC) systems producing electricity from both fossil and bio-based fuels. This demonstration supported the mission of developing an efficient, cost effective electricity source with near-zero water consumption, and low atmospheric emissions of CO₂ or other air pollutants, that can potentially operate on a wide range of domestic renewable or nonrenewable carbon fuels. The program consisted of five tasks, including:

Task 1. Project Management, Planning, and Reporting

Task 2. Site Selection

Task 3. System Design and Fabrication

Task 4. Stack Fabrication

Task 5. Demonstration

As a result of the DOE FY11 Fuel Cell Peer Review, a feature summary of the commercial potential of the TMI residential system was prepared and included under Task 1. During the Task 2 site selection, TMI completed a preliminary evaluation of approximately 44 different customer sites and ultimately selected Patterson's Farm Market of Chesterland, Ohio. Under Task 3, two 1-kW systems were fabricated and customized to the customer site. The systems were designed to accommodate natural gas, propane, and biodiesel fuel operation and electrical and thermal loads. Approximately eight sets of stacks were fabricated under Task 4 to support the demonstrations. The Task 5 demonstration was held at Patterson's Fruit Market and was open to the public during the first quarter of 2012. Most of the operation was on bottled propane because of site restrictions but TMI also operated on biodiesel as a proof of concept. During the demonstration, employees of Patterson's Market conducted their normal daily tasks around the system and TMI estimates that several hundred people saw the system in operation. Based on the test results, TMI believes *> 30% net electrical efficiency at 1 kW on both traditional and renewable fuels with a reasonable entry price is obtainable*. As a result of this demonstration, TMI initiated several engineering modifications, particularly to reduce the acoustic signature of the system. This change is expected to enhance customer acceptance and will be completed in 2012.

1.0 Introduction

Technology Management, Inc., (TMI) of Cleveland, Ohio is a developer of solid oxide fuel cell systems. Under this program, entitled “Small Scale SOFC Demonstration using Bio-based and Fossil Fuels,” TMI has engineered and demonstrated a kilowatt scale¹ solid oxide fuel cell (SOFC) system producing electricity from both fossil and bio-based fuels. This demonstration supports a mission of developing an efficient, cost effective electricity source with no water consumption, low atmospheric emissions of CO₂ or other air pollutants, and the potential to operate on a wide range of domestic renewable or nonrenewable carbon fuels.

The demonstration heavily leveraged existing programs and expanded on technology now being developed by TMI. The ability to switch among fossil fuels, biofuels and bio-derived fuels on the same fuel cell system presents high value propositions to both residential end users and small commercial businesses since the technology can be used to augment or replace existing utility grid power in the short run but also provides a clear, long term transition path to zero-carbon fuels and energy independence. Operating in parallel, the TMI modular fuel cell systems can facilitate the transition from fossil to bio-based fuels in increments, adding more power in smaller 1-kW steps.

Relative to the primary mission of the DOE Fuel Cell Program, the TMI SOFC system is potentially a ‘drop-in’ distributed generation subsystem that can be grid-independent and/or grid-connected which operates on fossil fuels as well as on various bio-based fuels, with zero water consumption and no air pollutants. The TMI fuel cell system is at the engineering system prototype stage in the 1-5 kW scale, and may contribute improvements to fabrication and operation on a proffered biofuel.

The primary outcomes of the project were technical feedback for TMI engineers to begin to optimize the system for a commercial product application. There are few practical alternatives for ordinary consumers to obtain all *their home electric energy from zero carbon biofuels*. Actual operating experience in a non-laboratory setting is crucial to establishing viable pathways to market for future product embodiments.

The critical component for this program is the unique TMI solid-oxide fuel cell integrated module, shown schematically in Figure 1, which operates on almost any available fuel. Most residential systems would use two to four 1 kW modules to provide continuous 24/7 electricity and heat for the electric power and hot water needs of the home plus a significant fraction of its space heating. Excess power could be available to be exported to the grid whenever necessary or economically prudent, thus providing the equivalent of massively distributed power storage.

¹ A kilowatt system produces about 720 kilowatt-hours of electricity a month (24x30), which is more than the baseload of an average US home or farmhouse.

Figure 1. Residential Fuel Cell-Grid Interconnection System Schematic.

The TMI SOFC, with and without thermal cogeneration, can achieve high efficiencies. In most of the United States, annual space heating needs are considerable and the resulting projected annual average energy utilization efficiencies of these systems are approximately 90% lower heating value (LHV). The mature product average AC/LHV efficiency is projected to be over 40% when no heat recovery is needed.

TMI SOFC modules have proven operation on renewable fuels, thus the proposed system is easily convertible to biofuels once it becomes commercially available shown in Figure 2.

Potential renewable biofuels include vegetable oils and biodiesel, including oils and esters of non-edible plants such as jatropha, biogas (bio-methane), and other bio-hydrocarbons (produced from gasified biomass and catalytic synthesis processes like Fischer-Tropsch). The DC power producing fuel cell system can also offer good synergy with optional solar photovoltaic panels, potentially sharing batteries and power conversion. At the 1-2 kW size, the TMI solid oxide fuel cell system is more efficient than a comparable diesel genset, with less noise and pollutants. In practice, diesel gensets are generally not available at the 2 kW size and instead, larger systems are 'de-rated' and operated at a lower operating output power. This relationship is shown graphically in Figure 3. In all practical conditions, the fuel efficiency of the fuel cell system is at least 50% greater, and given the relative size difference, can be nearly double.

Figure 2. Hal & Melinda Dalton with TMI Fuel Cell System Operating on Soybean Oil at Dalton Farms, Wakeman, OH, Apr/May 2009.

Figure 3. Relative Efficiency – Fuel Cells vs. Diesel Gensets.

1.1 Program Plan and Schedule

For this program, the original schedule with five tasks and associated milestones were proposed and shown below:

Tasks	Year 1											
	1	2	3	4	5	6	7	8	9	10	11	12
Task 1.0 – Project Management and Planning												
Task 2.0. Site Selection.												
Subtask 2.1: List of potential sites												
Subtask 2.2: Rank Order Sites.												
Subtask 2.3: Site Visits and Selection.												
Task 3.0. System Design and Fabrication.												
Subtask 3.1. System Engineering:												
Subtask 3.2. System Modification/Assembly/Pre-Testing:												
Subtask 3.3. Testing with Smart-Grid Concept Technology:												
Task 4.0 Stack Fabrication												
Task 5.0. Demonstration.												
Subtask 5.1. Site Preparation:												
Subtask 5.2. Installation and Testing:												
Subtask 5.3. Decommission and Reporting.												
Milestones												
1. Presentation to DOE/NETL												
2. Site Selected and Final Review												
3. System Design Completed												
4. System Installed, Testing Initiated												
5. Final Summary and Report												

Figure 4. Program Schedule.

2.0 Task Summary

A summary of the results from each task is provided below.

2.1 Task 1.0 – Project Management and Planning

TMI maintained a Project Management Plan in accordance with the requirements of the DOE National Energy Technology Laboratory (DOE/NETL). TMI coordinated all project activities, submitted all required NEPA documentation, and received approval according to DOE guidelines. Fabrication of the primary system component, the hot subassembly, was delayed due to issues associated with the fabricator. A no-cost extension was requested and granted postponing the program end date to March 31, 2012.

A site visit was held at DOE NETL, Pittsburgh on November 3, 2010, and the project was presented to the DOE NETL management team. The presentation included background information on TMI's organization, core technology, and systems development experience, the project's objectives, costs, risks, schedule, milestones, and status.

TMI participated in the DOE FY11 Fuel Cell Peer Review held in Morgantown, WV, on February 17, 2011. The presentation was made by Michael Petrik, VP/GM, with Dr. Robert Ruhl, VP-Technology and Project PI, in attendance. The Peer Review format was primarily set up to review progress during government fiscal year 2010, but because this program was not initiated until October 2010, (FY2011), TMI presented results through December 2010. Formal feedback was received from the review panel, TMI prepared the "RESPONSE TO RECOMMENDATIONS AND ACTION ITEMS FORM" to address these items. Many of the items were beyond the scope, budget, and intent of the original congressionally directed program, but TMI identified two areas that were examined prior to the completion of the project: i) identification of long term risk areas associated with commercialization of the technology, and ii) evaluation of preliminary markets, potential competitive technologies, and commercial product roll out relative to commercialization of the technology. The summary results of this analysis is shown below (Task 1.1).

TMI presented a poster overview of the program at the 12th Annual SECA Workshop, held July 26-28, 2011, in Pittsburgh, PA. TMI also reviewed the DOE Fact Sheet describing the program to be included on the DOE website.

2.1 Task 1.1 –TMI Residential Cogeneration Systems (Peer Review Reply)

The planned first TMI commercial product is expected to be 2 kW natural gas cogeneration systems for residential use. The systems will be installed indoors to produce electric power, hot water, and space heating assistance and are expected to reduce annual energy costs, slash greenhouse-gas emissions and provide uninterruptible whole-house power during grid outages of any duration. The grid-interactive systems could profitably sell surplus power to the utility in most cases (where pricing is favorable).

The safe, quiet systems would use TMI's unique solid oxide fuel cell technology. The utility grid would normally serve as a "virtual battery", supplying peak power needs. During outages, a standby lead-acid battery bank would supply up to 10 kW of surge and peaking power. Nominal AC voltage would be 120/240 Volts. A 100-gallon hot water storage tank would supply ample hot water heated by the fuel cell system. By-product fuel cell heat would also help heat the home.

The uninterruptible power capability of the fuel cell systems would be superior to standby engine-generators, which are very noisy and require outdoor installation on concrete pads. Many engine generators use liquid fuel, which, during major emergencies, is difficult to maintain sufficient supply. Such generators also do not provide true uninterruptible power, but need a short time to start.

The TMI systems would also enable addition of solar photovoltaic panels at significant cost savings, since a major portion of the required power conditioning and grid interface equipment would already be part of the installed TMI system. TMI systems are expected to have excellent synergy with PV arrays, giving lower fuel costs and greenhouse emissions while providing uninterruptible power for unlimited duration. PV array installed costs have significantly declined and are forecast to continue doing so, making the shared subsystems more valuable. Staged PV additions would be practical, up to about 12 kW nameplate capacity.

The complete TMI system with cogeneration and hot water storage tank would occupy about eight square feet of floor space, typically in a basement near an outside wall. Installed cost would depend upon site-specific details, but early systems are expected to have typical installed cost slightly below \$20,000 (as discussed herein, leasing and buyback options are planned). The systems will have safety approvals and three-year warranties. All-inclusive service contracts will be offered, providing annual preventive maintenance, fuel cell stack replacements when needed, and breakdown maintenance with one-day response.

Each system will include a wireless data interface, which will allow homeowners to view and interact with operating data for any selected time period, including power generated, purchased, sold, and heat recovery. With fuel and power cost inputs to an on-site computer, cost savings can be computed. Smart metering can be used to automatically regulate export of surplus power or to load-follow with no export when electricity selling prices are not economical.

The expected electrical efficiency (AC power/natural gas lower heating value) will be 40 to 50%, depending upon power level. Typical summer energy efficiency (with water heating) will be 50 to 60%. Heating season energy efficiency will be up to 109% of lower heating value (99% of higher heating value). Annual average energy efficiency for a Cleveland example is slightly over 90% LHV. The fuel cell subsystem will operate from zero to 2.0 kW AC as desired. The inverter and grid interface are capable of operation up to 10 kW (and up to 12 kVA), with the extra power derived from the battery bank or from solar panels. The key benefits include:

- **Uninterruptible Power.** A TMI system with an installed cost near \$20,000 can take the place of a whole-house standby engine-generator of up to the same cost. The dollar benefits of uninterruptible power cannot be readily quantified, but a single multi-day power outage in cold weather can cost thousands of dollars.
- **Cost Savings.** Residential natural gas now costs far less than electric power per unit of energy and the difference is forecast to continually widen (Ref. 1). If half the fuel cell power were sold at an average price of 2.5 cents/kWh below retail purchase price, the average annual energy cost savings would be \$1137 per year over the period 2015-2035 (\$1044 in year 1), based on the forecast prices. These savings include no carbon-avoidance credits or photovoltaic power. Annual all-inclusive service contracts are

expected to cost the user about \$200 per year, for average annual net operating savings of \$937 per year.

- **Greenhouse Gas Reduction.** Each TMI fuel cell system could reduce CO₂ emissions 15.3 tonnes/year (80% reduction from coal-generated power). Homes using less than 1.6 kW and selling 0.4 kW or more would thus be net negative for their carbon emissions for electric power.
- **Energy Efficiency.** The annual-average energy efficiency (about 90% LHV) of the TMI systems is projected to be about 2.5 times the average efficiency of utility power generation, thus helping to conserve finite natural resources.

The initial target market is single-family homes with natural gas in the northeastern quarter of the United States with moderate to high family incomes (an initial market size of over 4 million homes). Nominal market penetration (less than 0.1%/year) is projected to be sufficient to achieve profitability.

The early buyers will be “innovators” (also called technology enthusiasts), who give extra weight to the non-financial benefits such as uninterrupted power, carbon reduction, efficiency, and innovation. Many will also value the synergy with solar photovoltaics. Innovators are willing to take greater risks than the more numerous “early adopters”, who will follow later. Innovators can comprise at least 1% of the market, thus over ten times the number needed in the first profitable year.

Although the TMI technology is now fairly advanced, with multiple early demonstrations, necessary development work remains to be completed. Tasks include design for manufacture, component and subassembly alternatives evaluation, cell improvements, and system design refinements. Additional system demonstrations and extended runs are needed to validate changes and improvements. Although development work is a necessary ongoing activity for any technology-based product line, some further progress beyond today’s level is a prerequisite to early commercialization in order to ensure adequate performance in field testing.

TMI plans to partner with a sizeable corporation that has expertise in quantity manufacturing of complex products with at least some elements in common with the fuel cell systems. Possibly a second partner would assume manufacturing responsibility for the thermal (cogeneration) subsystems. Major subcontractors would also be sought to mass produce key components (e.g., power conditioning circuits, blowers, etc.). Both quality and cost would be emphasized. The manufacturing partner(s) must be based in the U.S. in order to allow close collaboration and product evolution.

TMI plans to partner with a leader in home energy systems for sales and marketing. Such a partner would have an established network of dealers capable of field installations and service. Minor field service of installed systems would be performed on site. Any major service needs would be accomplished by swapping major subsystems and returning the removed unit to the factory or a service depot for expert repair or renewal (including fuel cell stack replacements averaging every five years).

A disruptive new product such as this, not currently being sold, faces two major classes of risk, performance risks and cost risks. Performance risk is the chance that the installed product fails to achieve or exceed advertising claims and customer expectations for reliability, efficiency, noise, and convenience. The mitigation strategy for this risk is to perform approximately 25 field tests for up to a year or longer in actual homes. Pre-production systems will be modified to correct problems as needed and resume testing. TMI and its partners would offer all-inclusive service contracts to shift performance risk from users to the manufacturer, thereby achieving confidence in product performance before beginning large quantity manufacturing.

The cost risk means that success ultimately depends upon achieving and maintaining profitability, which in turn depends upon these key costs:

- **Installed Equipment Cost** must be attractive to the buyer when perceived financial and non-financial values are compared with other options (including possible future competitive systems). The risks of excessive installed costs include the following four components, with their risk mitigation strategies:
- **Equipment Costs** will be minimized by design for manufacture, automation added in stages as volumes increase, and by component development work to progressively lower costs. Assembly and all key manufacturing work will be performed in the U.S., with imported components and materials used only where necessary. Manufacturing engineering will be an ongoing activity to reduce costs, improve reliability, and improve product performance.
- **Installation Costs** will be minimized by crew training and the learning curve over an increasing quantity of installations. The goal will be to complete a standard installation in a single day with a two-person crew, similar to installation of residential HVAC systems.
- **Maintenance Costs** will be minimized by product design and component improvements during the product development period. Superior follow-on products may be swapped for installed early products to improve reliability. Fuel cell stack life is expected to improve with time, with the first set of replacement stacks lasting about 5 years, whereas the initial set may last only 3 years.
- **Competing System Costs** are a future risk. At present, no 2 kW residential cogeneration systems are offered for sale in the U.S. and none are expected soon. However, small fuel cell cogeneration systems are being installed in Japan today and eventually are expected to be offered here, as are systems from Europe, China, and Australia. Engine-generator systems compete for backup power, but not for continuous cogeneration. Backup generators sell for under \$1000 (small portable gasoline units) to as high as \$20,000 (whole house generators with automatic switching using natural gas, propane, or diesel), but are for intermittent use only and do not perform cogeneration. Engine-generator systems will not reduce electric power costs or greenhouse gas emissions.

System buyers can be offered several options to make first costs and ongoing risks more attractive. These may include extended warranties, maintenance contracts, alternative leasing and financing concepts.

2.2 Task 2 - Site Selection.

Site selection activities were performed to identify a willing potential end-user for the 30 to 90 day demonstration under this project. TMI selected sites based on multiple criteria with the most important being (a) end-user willingness to actively participate in the process of locating, installing, demonstrating, and promoting public relations activities, (b) a secure location with 24/7 accessibility to TMI employees, and (c) distance from TMI for ease of installation and ongoing monitoring/operation. In addition, location of the site within Ohio Congressional District 14 was preferred.

Initial activities involved the development of a list of potential sites and end-users. Assistance was sought from the Ohio Farm Bureau Federation and other consultants to identify rural end users that may have interest in biofuels and environmentally-conscious energy production. Table 1 and Figure 5 show the initial list of potential sites.

Figure 5. Map of Potential Demonstration Sites.

With so many potential options available, the decision was made to initially review sites that were recommended by advisors first, particularly sites that were closest to TMI. In addition, once two viable sites were identified, no additional site reviews would be performed.

Recommendations were received from the Ohio Farm Bureau Federation, TMI consultants and contacts for three sites – Grand River Cellars Winery (Madison, 32 miles), Patterson Fruit Farm

(Chesterland, 7 miles), and Gates Mills Environmental Education Center (Gates Mills, 6 miles) – and these sites were evaluated first.

Prior to visiting prospective sites, a presentation was prepared to provide background information to the end-users. The presentation provided basic background information about fuel cells, operation on renewable fuels and TMI, examples of previous off-site tests, information about the DOE demonstration project, site considerations, requirements and expectations. A sample of the presentation was provided to the Department of Energy during the course of reporting (January 25, 2011).

Table 1. List of Potential Demonstration Sites

1	Geauga Parks District	9160 Robinson Road	Chardon, Ohio
2	Orchard Hill Park	11340 Caves Road	Chesterland, Ohio
3	Sunnybrook Preserve	12474 Heath Road	Chesterland, Ohio
4	The Rookery	10110 Cedar Road	Munson Twp, Ohio
5	Bass Lake Preserve	11445 Lakeview Drive	Munson Twp, Ohio
6	Cleveland Botanical Garden	11030 East Boulevard	Cleveland, Ohio
7	Century Village	14653 East Park Street	Burton, Ohio
8	Geneva State Park	4499 Padanarum Road	Geneva, Ohio
9	James Garfield Museum	8095 Mentor Ave.	Mentor, Ohio
10	Punderson State Park	11755 Kinsman Rd	Newbury, Ohio
11	Holden Aoretum	9500 Sperry Road	Kirtland, Ohio
12	Great Lakes Science Center	601 Erieside	Cleveland, Ohio
13	Cleveland Metroparks Zoo	3900 Wildlife Way	Cleveland, Ohio
14	Sunrise Farm	13115 Kinsman Rd.	Burton, Ohio
15	Sirna's Farm and Market	19009 Ravenna Rd.	Mantua, Ohio
16	Patterson's fruit farm	11414 Caves Rd.	Chesterland, Ohio
	Patterson's fruit farm	8765 Mulberry Rd	Chesterland, Ohio
17	Gates Mills Environmental Education Center	390 County Line Rd	Gates Mills, Ohio
18	Eddy's farm	12079 Caves Rd	Chesterland, Ohio
19	Silver Rose Alpaca farm	10005 Kinsman	Novelty, Ohio
20	Old Firehouse Winery	5499 Lake Rd	Geneva on the Lake, Ohio
21	Chalet Debonne Vineyards	7743 Doty Rd	Madison, Ohio
22	Ferrante Winery	5585 Rte. 307	Harpersfield, Ohio
23	Grand River Cellars	5750 Madison Rd.	Madison, Ohio
24	Old Mill Winery	403 S. Broadway	Geneva, Ohio
25	The Lake House Inn Winery	5653 Lake Rd. E.	Geneva on the Lake, Ohio
26	The Winery at Spring Hill	6062 S. Ridge Rd. W.	Geneva, Ohio
27	Virant Family Winery	541 Atkins Rd	Geneva, Ohio
28	Lake Farm Park	8800 Euclid Chardon Rd	Kirtland, Ohio
29	The Indian Museum of Lake County	25 Public Square	Willoughby, Ohio
30	Lost Nation Municipal Golf Course	38890 Hodgson Rd	Willoughby, Ohio
31	Johnny Cake Ridge Golf Course	7134 Mentor Ave	Willoughby, Ohio
32	Newell K. Whitney Store	8876 Chillicothe Rd.	Kirtland, Ohio
33	Classic Airport	38630 Jet Center Dr.	Willoughby, Ohio
34	Fine Arts Association	38660 Mentor Ave	Willoughby, Ohio
35	Penetentiary Glenn Reserve	8668 Kirtland Chardon rd.	Willoughby, Ohio
36	Historic Kirtland Visitor Center	8876 Smith St,	Willoughby, Ohio
37	Stone Water Golf Club	1 Club drive	Highland Hts., Ohio
38	The Country Club	2825 Lander Rd.	Pepper Pike, Ohio
39	Cantebury Golf Club	2200 S. Woodland Rd	Shaker, Ohio
40	Auborn Springs Country Club	10001 Stafford Rd	Chagrin Falls, Ohio
41	Tanglewood Country Club	8745 Tanglewood Trl	Chagrin Falls, Ohio
42	South River Winery	6062 South River Rd	Geneva, Ohio
43	Highland Golf Course	3550 Green Rd	Shaker, Ohio
44	Berkshire Hills Golfcourse	9760 Mayfield Rd	Chesterland, Ohio

Visits were made to Patterson Fruit Farm (Figure 6) and the Gates Mills Environmental Education Center (GMEEC) (Figure 7) due to the distance from TMI offices and the nature of and/or relationship to the owner/operators (William Patterson is the President of the Geauga County Section of the Ohio Farm Bureau and GMEEC is managed by the Mayfield City Schools, which previously hosted a 3-day test of a TMI fuel cell system at one of their sites). Both sites had acceptable characteristics as outlined in Table 2 and accepted TMI's invitation to be a potential demonstration site.

Figure 6. Patterson Fruit Farm, Chesterland, Ohio.

Figure 7. Gates Mills Environmental Education Center, Gates Mills, Ohio.

Table 2. Demonstration Site Characteristics

Characteristic	Patterson Fruit Farm http://www.pattersonfarm.com/	Gates Mills Environmental Education Center http://www.mayfieldschools.org/exceltecc/w/btecc/environment.htm
Location	7 miles from TMI	6 miles from TMI
Fuels	Natural Gas, Propane, Heating Oil, Diesel available on site. Can bring in Vegetable Oil or Biodiesel	Natural Gas available on site. Can bring in Propane, Heating Oil/Kerosene, Vegetable Oil, or Biodiesel
Access	24/7 Access available at multiple locations on farm, all with reasonable security	24/7 Access available with high level of security
Electrical Loads	Multiple load opportunities depending on final siting. Loads included storage unit defrosting systems, lighting, refrigeration, farm-related systems	Multiple loads opportunities depending on final siting. include computer laboratories, lighting, green house systems, vending machines, refrigerators
Telecommunications	On-site WiFi available	On-site WiFi with additional on-site video monitoring available
Publicity	Willingness to independently promote demonstration; siting will provide public examination of test system	Willingness to independently promote demonstration; siting will provide educational opportunity to students
Owner Cooperation	Enthusiastic owners and staff. Owners have excellent contacts with city/county officials for final approvals of any necessary site considerations. Staff willing to assist in monitoring and operation. Owners are also available for any visits from DOE or other federal/state government officials	Enthusiastic management and staff. Management will lead interactions with local officials for final approvals of any necessary site considerations. Staff and students willing to assist in monitoring and operation of systems. Management is also available for any visits from DOE or other federal/state government officials

Site requirements for both the Patterson's Fruit Farm and Gates Mills Environmental Center were examined and found to have minimal impact on the overall system design. Two particular issues were identified: 1) the need to operate on both gaseous and liquid fuels to accommodate power generation with both bio-based and conventional fuels, and 2) operations and safety considerations. To operate on multiple gaseous and liquid fuels, the basic system must be modified to include both a mass flow controller for gases and a solenoid pump for liquids. The basic plumbing must also be modified to provide manual by-pass of either fuel control subsystem. The overall control system was also modified to allow selection of multiple liquid or gaseous fuels. The fuel selection control function provides calibration constants for either the pump or mass flow controller necessary for maintaining proper flow rates to the reformer and fuel cell stacks. In addition, other fuel characteristic constants, such as lower heating value and

stoichiometric charge, are provided for the specific fuel in order to calculate fuel utilization and efficiency.

Patterson's fruit farm was selected for the demonstration system due to the commercial nature of the enterprise and direct access to all necessary decision makers. Results of the demonstration are given below in Task 5.

2.3 Task 3 - System Design and Fabrication.

Under this program, two 1 kW systems were fabricated based upon site selection and pre-existing engineering designs and options. The systems

were designed to accommodate both fossil and bio-based fuel operation and loads associated with the site. The TMI SOFC system consists of a Hot Subassembly, Balance of Plant Components, and Ancillary Systems.

The fuel cell system design, particularly with respect to the hot subassembly, is directly leveraged to existing systems that are currently being developed for military applications in conjunction with funding from the Ohio Third Frontier (OTF) Fuel Cell Program through Lockheed Martin (Akron, Ohio). An overall CAD view of the hot assembly design is shown in Figure 8. The hot

subassembly is the heart of the TMI fuel cell system and houses the steam reforming subsystem, fuel cell stacks, and integrated heat exchange systems. The Hot

Subassembly system provides the stack with the proper operating environment for optimal performance through the integration of multiple complex functions. This subassembly mechanically holds the stack in place, removes heat to maintain stack temperature, heats the

incoming air prior to entering the stack, heats the reformer and vaporizer entirely by exhaust heat to provide gaseous-state fuel to the stack, and provides the electrical connections to the stack.

All heat required for air pre-heating, steam production, and steam reforming is provided by the Hot Subassembly's integrated internal heat exchange. To facilitate this simple implementation, TMI has developed a reforming catalyst capable of continuous operation on sulfur-bearing heavy hydrocarbons. Thermocouples within the Hot Subassembly are used to control the temperature of the unit.

Figure 8. TMI SOFC Hot Assembly.

The Balance of Plant consists of the water/fuel subsystem, exhaust condensers, power conditioning, and data acquisition/control systems. The fuel/water subsystem for operation on liquid fuels utilizes small variable-speed, positive displacement pumps to deliver variable flows for both fuel and water. A mass flow controller is used for gaseous fuels. A fan-cooled exhaust condenser provides the required reforming water from the hot exhaust stream and recycles the water to the vaporizer assembly. Careful thermal packaging ensures the system is water neutral under a wide range of conditions. Power conditioning utilizes custom electronics to convert stack DC power into useable voltages for on-board components. A microprocessor controller provides the overall operational logic and data acquisition functions.

For this program, design work was performed on the balance of plant systems, overall system layout, and control interface with particular consideration given to the needs of the customer site in regards to safety and fuels availability. As indicated above, the primary change for these demonstration systems was the need to operate on both gaseous and liquid fuels and the integration of the additional fuel mass flow controller components and associated plumbing, wiring and controls. The current design of the system places the hot subassembly side by side with the balance of plant components (Figure 9). The overall size of the system is approximately 16" x 32" x 36" – approximately the size of a two-drawer file cabinet. Fluid flow systems and the control and control/data acquisition system/interfaces are in the bottom section. On board power conditioning, battery storage, DC-AC inverter, and start up subsystems are located primarily in the middle section. Exhaust condensers are located in the top section.

Figure 9. Overall System Layout Design.

Ancillary Systems include start up components, DC-AC inverter, packaging/structure and external interfacing for electrical load, fuel supply, and safety systems. These components were included to insure the fuel cell system has minimal impact to site operations and provides a high degree of system safety. Custom electronic boards were designed and fabricated (Figure 10) to accommodate these concerns. Electrical loads to be powered by the fuel cell system were selected and isolated from

Figure 10. Custom Electronics Board Fabrication in Process.

the grid using an independent power strip. An external combustible gas detector, sensitive to hydrocarbons, hydrogen, and carbon monoxide, was installed to monitor the area around the fuel cell for any fuel leaks or abnormal exhaust leaks. The system was initially tied into the site's existing security monitoring system or connected directly to an automatic shut off valve, depending on the specific requirements of the end-user.

The control system used a National Instruments compact reconfigurable I/O (CompactRIO) module with and on-board real time processor and swappable I/O modules for processing both analog and digital signals. The CompactRIO system allows on-board continuous operation but is monitored by an external laptop with the user interface. An example of the user interface is shown in Figure 11. The user interface provides real time monitoring of temperature, pressure, flow, fuel cell performance data (voltages, current, efficiency), and alarm conditions. The user interface also allows the input of calibration data for various fuels and/or alternative fluid moving components. Data was recorded on a user selected time basis and is stored in the external computer for later evaluation. The laptop was then connected via WiFi to a broadband internet connection for remote monitoring.

Figure 11. TMI Demonstration System User Interface Example

The overall structural chassis/outer enclosure was fabricated using sheet metal with louvers for directing air flow. The final packaging for both systems is shown in Figure 12.

Figure 12. Completed Demonstration Systems without Hot Subassemblies.

2.4 Task 4 - Stack Fabrication

The fuel cell system begins with a stack. Figure 13 shows the TMI electrolyte-supported SOFC single cell and stack configuration. Each cell is made up of four layers: (1) a porous metal-ceramic anode that provides both fuel gas distribution and electrical continuity; (2) a pre-sintered, non-porous, YSZ electrolyte for selective ion conduction; (3) a fused, porous lanthanum strontium manganite (LSM) cathode that provides air distribution and electrical continuity; and (4) a non-porous high-temperature metallic alloy separator for bipolar electrical conduction from cell to cell. The cell, at 56mm (2.2 inches) diameter is approximately full commercial scale. These planar cells are stacked to achieve higher voltage and power. Multiple stacks can be used as power requirements increase. Holes in the center of each cell stack provide the manifolding for the fuel and oxidant. In each cell, fuel and oxidant are supplied through their respective holes and flow radially outward through the porous electrode pathways. This internal manifolding minimizes the seal perimeter area between the fuel and oxidant. At the circumference of the stack, depleted fuel and excess oxidant react completely before exiting as exhaust.

Figure 13. TMI Stack and Flow Schematic.

Approximately twelve kilowatts worth of SOFC components and stacks were produced for engineering studies, system development, and the demonstration. Under this program, TMI produced approximately 6000 cells and eight sets of stacks. Because of the infancy of the industry, the stack remains fundamentally a collection of best effort batch jobs; no reliable suppliers of any cell components at scale are available to meet the cost and quality issues. At the time of construction, the stacks represented the best available technology and were capable of unattended operation and operation on multiple fuels. Sample finished stacks are shown in Figure 14.

2.5 Task 5 - Demonstration

After a thorough search, Patterson's Fruit Farm (<http://www.pattersonfarm.com/>) was selected as a primary site for the demonstration. Patterson's offers a collection of services for the Cleveland community and east suburbs year round including local produce and other products and services. As a local business (Figure 15), Patterson's was interested in both evaluating alternative energy concepts, particularly those involving renewable fuels, and assisting TMI in evaluating its system in a light commercial setting.

Figure 14. First Set of TMI Stacks Produced.

Figure 15. Location of Patterson Fruit Farm (Chesterland, Ohio).

The demonstration was conducted using two 1-kW systems over the first quarter of 2012. A complete discussion is given below while Table 3 shows a summary of the peak performance of the first system on natural gas. This test indicates that the TMI SOFC has the potential to achieve the necessary high net efficiencies ($>30\%$) to be viable in the stationary distributed generation market. As discussed below, owing to limited maturity of the system, a number of electrical and flow problems compromised the ultimate system efficiency.

Table 3. Peak System Performance

Gross Power (W)	Net Power (W)	NG Flow (lpm, corrected)	DC Eff (%)	Net Eff (%)
759	570	2.9	43.0%	32.3%
895	710	4.3	34.3%	27.2%
1099	836	5.4	33.5%	25.5%
Maximum Projected Performance				
1355	1092	5.4	41.3%	33.3%

Both 1-kW systems were ultimately benchmarked on both propane and biodiesel as well. Performance on propane, as expected, was very similar to natural gas. On biodiesel, the system demonstrated a performance of 713 W at approximately 80% of full flow with 62% fuel utilization. BOP issues relating to thermal management and heat exchange caused difficulties in achieving the full target operation. As mentioned above, the demonstration clearly indicates the promise of the technology but also indicates that additional engineering improvements are required to achieve optimal fuel cell operation in this environment.

TMI originally intended to operate on natural gas and biodiesel onsite for the demonstration. However, the local natural gas supplier was unable to provide a suitable natural gas supply in a reasonable time frame; thus TMI opted to take advantage of the multi-fuel characteristics of its system and operate on bottled propane instead. For the demonstration, two forty pound cylinders

were selected and operated in parallel with step down regulators used to allow one tank to preferentially be emptied and replaced while the second tank seamlessly supplies the system. For safety reasons, TMI installed a propane cabinet on the outside wall of the market, as shown in Figure 16. The cabinet included regulators, temperature measurements, and inclement weather protections.

Marketing and informational materials were also prepared for the site. Arrangements were also being made to host Congressman Steven LaTourette (Congressman for Ohio's 14th District) for a visit of the system test at Patterson's Farm.

One system was benchmarked at TMI in January 2012 as described above in Table 3. The result of continuous load testing at approximately 60% of full flow for approximately 450 hours is shown in Figure 17. Overall, performance and stability were within minimum specifications for the demonstration and the system was moved to Patterson's farm and installed in the market (Figure 18).

Once installed, however, a number of problems occurred with the balance of plant (BOP). Water balance was difficult to maintain, despite relatively modest operating conditions and a cool, indoor environment. The system was unusually loud compared to normal operation as well. The root cause of these problems was ultimately traced to electrical connections on the compact RIO control card that had become loose during operation. The connections led to uncontrolled flow of the cooling compressor that forced the system onto the electric guard heater and ultimately lead to insufficient water balance, excessive thermal gradients, and a failed guard heater. The system was shut down at the site. TMI removed the system and reevaluated the BOP and control systems where upon the connection issues were discovered.

Figure 16. Location of Patterson Fruit Farm Farm Market (Propane Closet).

Figure 17. Benchmark Performance on System for Patterson's Farm.

Figure 18. Installation of System 1 at Patterson's Farm Market.

A second system, with improved electrical connections and additional sound dampening materials to help ameliorate the acoustic signature, was assembled at TMI and then installed at Patterson's Farm on January 23, 2012. At least one system operated on site continuously for 53 days to March 16th. A run chart of operation on propane for approximately the first 400 hours is shown in Figure 19. Once operation at Patterson's was completed for this system, the SOFC was returned to TMI for continuing evaluation. After several rudimentary checks, the system was switched to natural gas and left on continuous operation. This system has now logged in excess of 2700 hours of operation.

The first system was refurbished and a new stack installed in February. After additional benchmarking, the system was returned to Patterson's Farm where two systems were running concurrently during the visit by Congressman Steven LaTourette. Rep. LaTourette is shown with Michael Petrik, Vice President of TMI, in Figure 20. This system was operated on bottled propane on site until the end of March, whereupon the system was removed and returned to TMI for inspection. A partial run chart of its operation at TMI is shown in Figure 21. The jumps in auxiliary and gross current correspond to the water condenser fan switching from low to high speed. The overall performance was stable and predictable.

Figure 19. Benchmark Performance on System #2 at Patterson's Farm.

Figure 20. Two Systems at Patterson's Farm Market with Rep. Steven LaTourette.

Figure 21. Partial Operation Chart for Patterson's Farm (Feb/March 2012).

After two months of operation on site, some general themes were evident. Some of these observations are anecdotal, collected by word of mouth, and not quantified systematically. Issues that impacted testing and performance included: stack-to-stack performance variation, electrical noise, and audible sound.

Stack-to-Stack Performance Variation

Maximum system performance was hampered by stack-to-stack variations. For example, the system shown in Figure 17 had a variation from stack to stack power of over 30% at full flow and power condition. The stacks themselves are completely random and 75 cells, each so variations are largely believed to be because of flow distribution. Had all six stacks contributed equally, the peak performance would be calculated to have greater than a 10% increase in DC efficiency and 8% increase in net AC efficiency.

Stack-to-stack performance can be impacted by flow, temperature, or mechanical characteristics of the system. As indicated previously, the randomized, multi-cell nature of the stacks decreases the probability of particular cell issues causing major stack variations. Previous experience has indicated that stacks reactant distribution variations can also lead to electrical performance variations between stacks. Flow distribution is primarily a function of the mechanical design of the stack secondary air heat exchanger and the steam reformer. Because reactant flows not only impact flow into the stacks (and thus associated electricity and heat generating reactions) but also the primary heat exchange mechanisms, flow of reactants is also directly related to local temperatures (through localized heat transfer). Temperature variations within the hot subassembly can lead to electrical performance variations as well.

Because substantial performance differences were observed in the stacks, engineering design reviews of the major heat exchange subsystems were performed. Heat exchange subsystems examined included:

- Exhaust/Cathode Air Pre-heater
- Cathode Secondary Air Heat Exchanger
- Exhaust/Water Vaporizer/Superheater

All of these heat exchangers use narrow gap flow paths to improve heat transfer. A trade off of this strategy is the need to minimize pressure drop, particularly in the air and exhaust circuits in order to minimize parasitic power losses caused by compression. Based on the design review, the Cathode Secondary Air Heat Exchanger manifold was found to likely have insufficient pressure drop necessary to maintain uniform flow distribution around the stacks over the entire range of operating conditions. This situation caused uneven heat removal from the stacks, thereby leading to performance variation issues. Although beyond the scope of this program to implement, TMI was able to redesign the heat exchanger under another program in order to improve the flow uniformity while maintaining reasonable pressure drops.

A cross section of the modified heat exchanger is illustrated in Figure 22. The design used a single pass narrow gap with multiple distribution holes. The holes provide the pressure drop necessary for uniform distribution, while the narrow gap provides the improved heat transfer characteristics with the air. The potential risks to this design are fabrication related. The number of air holes is significant but the dimensions and distribution are not believed to be difficult to achieve within normal fabrication constraints. Alternative designs have been determined and preliminary fabrication has been initiated but were not available for this program.

Electrical Noise

An additional challenge was electrical 'noise' in the control circuitry. As shown above in Figure 11, a control interface was developed for autonomous operation. One of the tracking options developed is for the user to follow 'a peak efficiency' condition, changing fuel flow rate dynamically with user electrical loads. Unfortunately, significant electronic noise along the current-sensing circuitry prevented actual operation on fuel-tracking mode. Further, variation in the flow meters themselves complicated accurate analysis and required post-test evaluation and correction to validate accurate measurements. Additional noise filtering hardware will be added to future systems.

Audible Sound

Visitors to Patterson's Farm seemed to be sincerely interested in alternative energy. Largely, two groups of people seem to dominate. A first group was individuals who simply appeared to like the idea of 'cheaper, cleaner' power. They liked the concept of alternative energy and would generally support such a system as long as it didn't interfere with their day to day living or cost significantly more. The second group was the people who appeared to be interested in the novelty of the fuel cell technology and were curious about creative implementation of the technology. This latter group seemed most attracted by the small size and multifuel operation.

Employees voiced a complaint about the 'sound' of the system. The demonstration unit was installed at Patterson's in the pastry area of the market. The location was selected because of the proximity to the outside wall (for the propane fuel) and minimal interference with the market's general operation. In the quiet enclosed area, with little to no other sound producing sources, the constant hum of the compressors was an annoyance. TMI's earlier demonstration at Dalton's Farm was in a more open, rural area with other equipment and the sound was never identified as a problem.

This feedback is considered important customer feedback, so design modifications were made to reduce the sound. The original system had a constant sound of approximately 66 dB at < 1 m in the lab. This was reduced by approximately 3 db by including sound adsorbent foam. At the customer's site, TMI took measurements of the acoustically dampened system. A simplified

Figure 22. Cathode Secondary Air Heat Exchanger Design

sketch of the layout and corresponding sound measurements is shown in Figure 23. Although the system is certainly audible, the sound of normal conversation is approximately 60-65 dB. TMI will continue to evaluate the system and in an effort to make improvements to enhance customer acceptance.

Figure 23. Simplified Sketch of Patterson's Market Pastry Area

3.0 Conclusions

Technology Management, Inc. (TMI) of Cleveland, Ohio, engineered and demonstrated a 1-kW fuel flexible solid oxide fuel cell system operating on both traditional fuels and environmentally friendly biodiesel under the project entitled "Small Scale SOFC Demonstration using Bio-based and Fossil Fuels". Operation of several systems occurred primarily on bottled propane and biodiesel. A two month demonstration at Patterson's Farm Market of Chesterland, Ohio, a local environmentally-conscious business, was completed and quantitative and qualitative metrics were evaluated. This demonstration supported the mission of developing an efficient, cost effective electricity source with near-zero water consumption, and low atmospheric emissions of CO₂ or other air pollutants.

As a result of this demonstration, TMI has initiated several engineering modifications, particularly to reduce the acoustic signature of the system. This change is expected to enhance customer acceptance and will be completed in 2012. Additionally, TMI has begun to reassess all fluid pathways to improve stack-to-stack performance reproducibility. Based on the test results, TMI still believes *> 30% net electrical efficiency at 1 kW on both traditional and renewable fuels with a reasonable entry price is obtainable.*