

REBELS Program Overview

B. PROGRAM OVERVIEW

This program, Reliable Electricity Based on ELectrochemical Systems (REBELS), seeks to disrupt traditional learning curves for distributed stationary power generation, by introducing technology concepts that have the potential for significantly lower cost and that are capable of performance superior to current distributed generation technologies. Fuel cell technologies have been touted for decades due to their high chemical-to-electrical conversion efficiencies and potential for near-zero greenhouse gas emissions when fueled by hydrogen or operated as part of a carbon capture and storage (CCS) process. However, fuel cell technologies have not achieved widespread adoption due primarily to high cost relative to incumbent combustion technologies. In this program, ARPA-E seeks to fund transformational fuel cell devices that operate in an *intermediate temperature* range in an attempt to 1) create new pathways to achieve an installed cost to the end-user of less than \$1,500/kW at moderate production volumes,¹ and 2) create new fuel cell functionality to increase grid stability and integration of renewable energy technologies such as wind and solar.

Existing DOE programs in the Office of Energy Efficiency and Renewable Energy (EERE) and the Office of Fossil Energy have focused on low temperature proton exchange membrane (PEM) fuel cells and high temperature solid oxide fuel cells (SOFC) for transportation and stationary power applications, respectively. Over the past ten years, these programs have advanced PEM and SOFC technologies in both performance and cost. While the technologies that emerge from the REBELS program will be at earlier stages of their learning curves than current PEM and SOFC technologies, ARPA-E's view is that fuel cell operation in an intermediate temperature regime could enable unique opportunities for cost reduction and performance improvement with multiple pathways to market adoption. This program builds on materials advances over the past decade that have broadened the number of available electrolytes and electrodes beyond traditional PEM and SOFC temperature ranges. ARPA-E aims to bring together different scientific communities, such as fuel cell materials scientists, inorganic and polymer chemists, researchers working on novel approaches to activate carbon/hydrogen bonds for fuel processing, and experts in fuel cell fabrication methods to quickly advance intermediate temperature fuel cells to working prototypes and engage with stakeholders who can drive these devices towards market adoption. ARPA-E also aims to fundamentally alter the paradigm of fuel cell systems by creating new functionality in fuel cell technology such as battery-like response to transient loads and electrochemical production of liquid fuels.

CENTRALIZED STATIONARY POWER GENERATION: ADVANTAGES AND DISADVANTAGES

The current system for delivering electricity consists primarily of fuel-to-electricity generation at coal, natural gas combined cycle (NGCC), and nuclear plants, followed by transport across the U.S. electrical grid via transmission and distribution (T&D) networks, and finally delivery to the end-user. This baseload generation is complemented by spin reserves such as simple-cycle natural gas turbines that provide additional capacity during peak use hours, as well as other ancillary services such as voltage regulation, load following, system protection, etc. The primary benefit of this centralized approach to power generation is that the conversion of chemical energy to electricity via combustion or fission is more efficient and cost effective at scale. For example, a state-of-the-art 510 MW NGCC plant, can have electrical efficiencies on the order of 51-55% on a higher heating value (HHV) basis.² In contrast, smaller simple cycle gas turbines with a capacity of 1-10 MW have electricity efficiencies of roughly 21-29% HHV.³

Disadvantages of the current centralized electricity generation system include:

- Significant greenhouse gas emissions: more than 2 billion tons of CO₂ are released annually from the electricity production sector.⁴
- T&D losses and expenses: on average, 7% of the electricity produced in the U.S. is lost during transmission and distribution.⁵ This results in 218 million tons of CO₂ emissions (equal to 62 coal plants) and \$25 billion of lost

¹ "Installed cost to the end-user" includes cost of the complete system, tax, and markup; "moderate production volume" is defined as less than 50,000 units per year.

² http://www.netl.doe.gov/KMD/cds/Disk50/NGCC%20Technology_051507.pdf

³ "Catalog of CHP Technologies," U.S. Environmental Protection Agency Combined Heat and Power Partnership (2008).

⁴ <http://www.eia.gov/tools/faqs/faq.cfm?id=77&t=11>

⁵ <http://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3>

revenue.⁶ Additionally, an estimated \$1.5-2.0 trillion in T&D investments will be required between now and 2030 to build new power corridors and maintain existing ones.⁷

- Grid vulnerability due to natural disasters and terrorist attacks, including cyber attacks.⁸
- Difficulty in integrating renewable energy technologies, discussed in further depth below.

The Need to Integrate an Increasing Amount of Renewable Energy with the Grid

Installation of variable and intermittent generation technologies such as solar photovoltaic and wind turbines poses a fundamental challenge to centralized power generation. Matching generation and load in the grid becomes difficult with high levels of variable energy resources (VER) because they are non-dispatchable;⁹ vary on the time scales of minutes, hours, and days; and can unpredictably ramp up and down due to weather events. In addition, VER are located on the edge of the grid or far from load centers where inadequate transmission resources exist connecting the generation to the load. This is becoming an increasingly critical issue, as the installation of renewable electricity generators such as solar and wind is a growing trend in the United States,¹⁰ driven in part by renewable portfolio standards (RPS) in 27 states and net metering policies and other efficiency incentives in 43 states.¹¹

Today, integration of VER into the grid is usually accomplished by using dispatchable, quick-ramping thermal generators to smooth the variability over a “balancing region.” This preserves reliability, power quality, and counters VER ramp events and errors in weather forecasting.¹² Inadequate balancing reserves and/or transmission resources have already led to curtailment of renewable power in both the Electric Reliability Council of Texas (ERCOT) and the Bonneville Power Administration’s (BPA) system.¹³ In 2012, however, the Federal Energy Regulatory Commission (FERC) issued Order 764 which adopted reforms intended to better integrate VER with the grid.¹⁴

Addressing Challenges of the Grid through Distributed Generation

The challenges associated with centralized power generation described above indicate the potential for distributed generation (DG) to be a complementary and beneficial strategy for power delivery. There are over 12 million DG units in the United States, with a capacity greater than 200 GW.¹⁵ However, the majority of this capacity exists as emergency backup generators that are seldom operated. Nevertheless, increased DG in the U.S. would have multiple benefits, including peak load reduction, reactive power and voltage support, reduced T&D congestion, improved power quality, and reduced grid vulnerability.¹⁵ Many companies, including some large retail, technology, and manufacturing companies and the owners of large building complexes such as hospitals are implementing DG because of energy cost savings and increased reliability.¹⁶

Another benefit of DG is the capability to utilize waste heat generated in the process of converting chemical energy to electricity. Combined heat and power (CHP, or cogeneration) and combined cooling, heating, and power (CCHP, or trigeneration) has the potential to increase efficiency to greater than 80% at residential homes, commercial businesses, and industrial facilities. There is approximately 82 GW of CHP capacity in the United States,¹⁷ which reduces annual energy consumption by 1.9 quadrillion British Thermal Units (Quads) and CO₂ by 248 million metric tons.¹⁸ The White House is currently supporting a new challenge to install 40 GW of new, cost-effective DG by 2020. The expected benefits include \$10 billion in energy savings, 1 Quad reduction in energy consumption, and a CO₂ reduction of 150 million metric tons.¹⁷

⁶ Assumes 1.67 lbs. CO₂/kWh (average of coal and natural gas) and a retail electricity price of \$0.10/kWh.

⁷ “A Natural Gas Enabled Smart Grid: Opportunities for Distributed Energy Resources,” Dan Rastler, Electric Power Research Institute, presented at 13th Annual SECA Workshop (2012).

⁸ “Electric Grid Vulnerability: Industry Responses Reveal Security Gaps.”

<http://democrats.energycommerce.house.gov/sites/default/files/documents/Report-Electric-Grid-Vulnerability-2013-5-21.pdf> (2013).

⁹ R. Masiello, et al., “Research Evaluation of Wind Generation, Solar Generation, and Storage Impact on the California Grid,” prepared for the California Energy Commission (CEC-500-2010-010) (2010).

¹⁰ U.S. Energy Information Administration, “Annual Energy Review,” <http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf>, Figure 8.2a (2011).

¹¹ http://www.dsireusa.org/documents/summarymaps/net_metering_map.pdf

¹² “MIT Study on The Future of the Electric Grid,” <http://web.mit.edu/mitei/research/studies/the-electric-grid-2011.shtml> (2011).

¹³ R. Wiser and M. Bolinger, “Wind Technologies Market Report,” http://www1.eere.energy.gov/wind/pdfs/2011_wind_technologies_market_report.pdf (2011).

¹⁴ <http://www.ferc.gov/whats-new/comm-meet/2012/062112/E-3.pdf>

¹⁵ “The Potential Benefits of Distributed Generation and Rate-Related Issues that May Impede their Expansion,” U.S. Department of Energy (2007).

¹⁶ <http://www.fuelcells.org/uploads/BusinessCaseforFuelCells.pdf>; <http://www.modernhealthcare.com/article/20130907/MAGAZINE/309079851>

¹⁷ “Combined Heat and Power: A Clean Energy Solution,” U.S. DOE and EPA (2012).

¹⁸ “Combined Heat and Power: Effective Energy Solutions for a Sustainable Future,” Oak Ridge National Laboratory, ONRL/TM-2008/224 (2008).

Current fossil fuel DG technologies (or ‘prime movers’) include reciprocating engines, gas turbines, microturbines, internal combustion engines, and fuel cells. Each technology varies in terms of operational parameters such as: nameplate capacity, operating temperature, start-up time, electrical efficiency, CHP efficiency, installed cost, operations & maintenance (O&M) costs, and maintenance intervals. An end-user’s decision to install a particular DG prime mover will be based on these attributes, as well as factors such as technical requirements, fuel type, and geography, along with state and local incentives.

The Need for Small, Reliable Distributed Generation

Given Carnot limits for combustion technologies and traditional economies of scale, the efficiency of a DG unit generally increases and the installation cost decreases, as the overall system size increases. In fact, most units that demonstrate an electrical efficiency greater than 30% HHV and an installation cost lower than \$2,000/kW are 300 kW or larger. This is illustrated in Figure 1, where the desirable combination of cost and efficiency exists in the center of the figure. There is a noticeable gap as system size decreases.

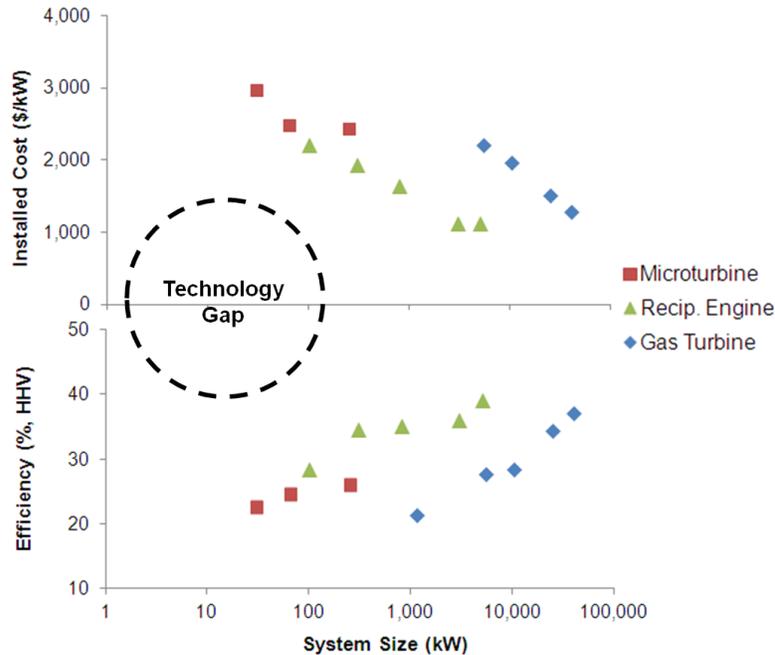


Figure 1: Installation cost and electrical efficiency of various DG prime movers as a function of system size, indicating a technology gap of low cost, high-efficiency prime movers at smaller sizes (adapted from³)

Another factor that has favored installation of larger DG units is maintenance intervals and the associated O&M cost. As shown in Table 1, the maintenance intervals for smaller DG prime movers such as microturbines and particularly reciprocating engines entail more frequent service for continuously operating generators. ARPA-E seeks a DG prime mover below 100 kW that has an optimal balance of high efficiency, low installed cost, and low maintenance requirements for long-term operation.

Maintenance Intervals (hrs)	
Gas Turbines	4,000-8,000
Microturbine	5,000-8,000
Recip. Engine	500-2,000 (inspection) 8,000 (overhaul)
Fuel Cells	20,000-40,000+

Table 1: Maintenance intervals for various DG prime movers³

There are several niche applications that could benefit from small, efficient, reliable DG and serve as potential first markets. One such example is backup power for telecommunications sites such as cell phone towers and call centers.

Fuel cells represent a superior option for such applications because they have lower emissions, are quieter, and require less on-site maintenance.¹⁹ Another potential early market for small fuel cell systems is electrification of natural gas wellpads. Because of the low value of ‘stranded’ natural gas, wellpads are currently operating by pneumatic devices that operate on the pressure of the gas. However, this gas is then vented to the atmosphere, resulting in more than 20 million

¹⁹ Fuel Cells for Backup Power in Telecommunications Facilities,” <http://www.hydrogen.energy.gov/pdfs/44520.pdf> (2009).

tons of CO₂ equivalent emissions and \$3.2 billion in lost revenue.²⁰ Reliable 3-5 kW fuel cells could be used to provide continuous power to the wellpad, reduce emissions, and recover lost revenue associated with vented gas.

Despite these promising applications, the potential performance improvements associated with fuel cells for small DG applications have yet to be fully realized due to cost and fuel supply barriers. First, fuel cells remain expensive, and cost/benefit calculations made by businesses are greatly affected by Federal, state, and/or local incentives. For example, the current Federal Investment Tax Credit (ITC) for fuel cells subsidizes 30% of the system cost or \$3,000/kW, whichever value is smaller. This ITC is valid for systems built until the end of 2016.²¹ Second, most of the fuel cell systems described above operate directly on pure hydrogen fuel that must be produced (typically via steam methane reforming), transported to the site, stored in gas tanks, and then refilled or swapped when empty. A simpler and longer-term option would be a direct connection to a natural gas line and use of an on-site fuel processor. This scenario would expand the functionality of fuel cells beyond backup power, provide superior reliability, and enhance siting flexibility for commercial installations such as telecom, data centers, etc. These first markets would enable a larger fuel cell supply chain and increased manufacturing volume, thereby establishing a pathway towards applications such as residential DG and CHP.

Closing the Cost and Performance Fuel Cell Gap

Electrochemical devices such as fuel cells are a potential solution for small, reliable DG because they are not limited by the Carnot cycle. The electrical efficiency of small fuel cell systems is typically 30-43% HHV, compared to small combustion technologies that do not exceed 30% HHV.³ While fuel cell efficiencies are typically lower than large NGCC power plants, additional factors mentioned above such as T&D losses, as well as gains due to CHP or CCHP configurations, mean that GHG emissions from small fuel cell systems can meet or be lower than the GHG emissions of the best centralized power generation technologies today, as shown in Figure 2. Additionally, the potential for ultra-low emissions from renewably-derived hydrogen fuel or as part of a CCS process means that fuel cells are likely to be a key technology for a zero carbon future.

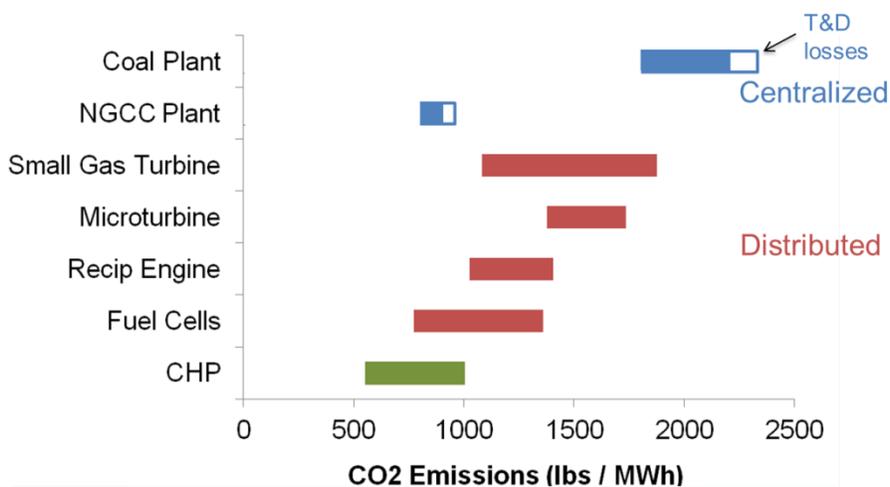


Figure 2: CO₂ emissions from centralized, distributed, and CHP generation technologies³

The U.S. government for many years has funded fuel cells and hydrogen storage research with a focus on transportation and stationary power applications. The materials emphasis of these programs has mostly been on high temperature SOFCs based on yttria-stabilized zirconia (YSZ) electrolytes and low temperature PEMFCs based on Nafion®. While progress has been made in improving the performance of both devices, state-of-the-art SOFCs and PEMFCs still face technical and commercialization challenges. The high operating temperatures and poor thermal cycling characteristics (> 700 °C) of SOFCs has confined them to steady-state, baseload applications, and also require high cost materials for the balance of plant.^{22,23} Traditional PEMFCs are restricted to low operating temperatures (< 100 °C) and require expensive platinum group metal (PGM) catalysts, ultra-pure hydrogen fuel, and a complex system for membrane hydration. PEMFCs

²⁰ "Petroleum and Natural Gas Systems 2011 Data Summary," EPA, <http://www.epa.gov/climatechange/Downloads/ghgemissions/2013Workshop/supporting-info-2011-data-summary.pdf>

²¹ http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=US02F

²² S.M. Haile, Acta Mater. 51 (2003) 5981-6000

²³ D.J.L. Brett, et al., Chem. Soc. Rev 37 (2008) 1568-78

also have issues related to long-term durability, corrosion, and fuel crossover.^{22,24} The strengths as well as challenges of these devices are summarized in

Table 2 below. Current fuel cell systems have an installed cost of at least \$4,000/kW,²⁵ which has limited their widespread adoption into the distributed power generation market.

Table 2: Advantages and challenges of low temperature PEMFCs and high temperature SOFCs

	PEMFC	SOFC
Strengths	<ul style="list-style-type: none"> • Rapid startup • Cycling ability • Roll-to-roll processing 	<ul style="list-style-type: none"> • High power density • Higher electrical efficiency • Inexpensive catalysts • Fuel flexibility
Challenges	<ul style="list-style-type: none"> • Expensive PGM catalysts required • Fuel limited to H₂ • Complex fuel processing required • Low quality heat for CHP 	<ul style="list-style-type: none"> • Performance & cost of interconnects and seals • Limited to static, baseload operation • Stack lifetime

Alternative fuel cell electrolytes and electrode materials do exist and can, in fact transport a wide variety of ionic species, including: oxide, hydronium, and carbonate ions, structural or defect protons, or other hydrogen carriers such as hydroxide, ammonium, or H₂S. Plotting the temperature of operation versus the ionic conductivity of several of the electrolytes, Norby identified a common deficiency in electrolyte performance, dubbed “Norby’s Gap,” in the range of 300-600°C.²⁶ In the 14 years since that paper was published, many new electrolyte materials with ionic conductivities >10⁻² S/cm in the range 200-600°C have been identified and several of these materials have been developed into full-scale fuel cell systems. Examples include solid acid fuel cells,²⁷ low temperature SOFCs,²⁸ intermediate temperature alkaline fuel cells,²⁹ and intermediate temperature proton conducting fuel cells.³⁰ Novel electrodes and electrolytes for intermediate temperature SOFCs were summarized in a recent review.³¹ These recent materials advances support the view that operation in an intermediate temperature range between traditional PEMFC and SOFC devices is possible, and could afford lower cost systems for small DG applications.

The benefits of operation in an intermediate temperature range higher than traditional PEMFCs (> 100°C), include the use of simpler and lower cost fuel processor subsystems by incorporating some degree of in-situ fuel reformation, as well as reduced fuel purity requirements due to a greater tolerance to CO and other reformat impurities. Conventional thinking has held intermediate temperature operation to be incompatible with fuel flexibility, as formation of coke from hydrocarbons becomes increasingly favorable below 650 °C. That may be the case for traditional Ni/YSZ composite anodes, but there are multiple concepts using CeO₂-based systems,^{32,33} as well as biological approaches to C/H bond activation³⁴ that could enable intermediate temperature fuel processing. On the other hand, operating below traditional SOFC operating temperatures (< 650°C) could enable the use of lower-cost interconnects and seals, and increase stack lifetime. Other potential benefits of intermediate temperature operation are summarized in Table 3. While ARPA-E recognizes that intermediate temperature operation is not a solution for all fuel cell cost and performance issues, the combination of lower cost materials, simpler balance of plant, and more dynamic operation suggests great opportunity in this technology space.

²⁴ B.C.H. Steele, A. Heinzl, Nature 414 (2001) 345-52

²⁵ National Fuel Cell Research Center, University of California-Irvine, http://www.nfrcr.uci.edu/2/FUEL_CELL_INFORMATION/FCexplained/challenges.aspx

²⁶ T. Norby, Solid State Ionics 125 (1999), 1-11.

²⁷ <http://www.technologyreview.com/news/421277/cheap-diesel-powered-fuel-cells/>

²⁸ E.D. Wachsman, et al., Science 334 (2011) 935-939.

²⁹ T. Hibino, K. Kobayashi, J. Mat. Chem. A 1 (2013), 1134-1140.

³⁰ Y. Huang, et al., J. Mat. Chem. 22 (2012), 22452-22458.

³¹ A. Aguadero, et al., J. Mater. Sci. 47 (2012), 3925-3948.

³² T. Suzuki, et al., Energy & Env. Sci. 4 (2011) 940-943.

³³ H. Zhu, et al., Int. J. Hydr. Energy 38 (2013) 3741-3749.

³⁴ V. Dong, “Methane Activation: Inspiration from Nature,” [http://arpa-](http://arpa-e.energy.gov/sites/default/files/documents/files/2_Methane%20activation%20inspiration%20from%20nature%20-%20Dong.pdf)

[e.energy.gov/sites/default/files/documents/files/2_Methane%20activation%20inspiration%20from%20nature%20-%20Dong.pdf](http://arpa-e.energy.gov/sites/default/files/documents/files/2_Methane%20activation%20inspiration%20from%20nature%20-%20Dong.pdf)

Table 3: Potential benefits of fuel cell operation in an intermediate temperature range

Potential benefits of intermediate temperature operation	
Compared to low temperature FCs	Compared to high temperature FCs
<ul style="list-style-type: none"> • Simpler fuel processor design • Greater tolerance to CO and other impurities • Lower or zero need for PGM catalysts • Increased fuel flexibility • Greater CHP potential 	<ul style="list-style-type: none"> • Reduced interdiffusion and interfacial reaction product formation • Reduced degradation from differences in thermal expansion coefficients at interfaces • Ability to operate dynamically • Lower cost interconnects and seals • Longer stack lifetime • Reduced coarsening of nanostructured materials

Increasing Fuel Cell Functionality: The Potential to Ease Renewables Integration with the Grid

The concept of stationary fuel cells reducing grid instability has been explored in the past, with focus on demand control techniques, DC-DC converters, changes in steady-state fuel utilization, and integration with batteries or ultracapacitors.^{35,36} For example, Meacham and coworkers modeled fuel cell ramp rates ranging from 0.01 to 100 kW/s and concluded that a fuel cell system without energy storage would have to respond at a rate of approximately 100 kW/s to avoid perturbing the grid. Such ramp rates are highly unlikely based on traditional fuel cell technologies, as fuel starvation and thermal fluctuations would likely occur due to fuel flow delays associated with the slow response of the fuel processor.³⁷ An expansion of fuel cell functionality beyond the DG/CHP scenarios outlined above could increase the benefits of fuel cells as a complementary technology for integrating renewables with the grid. One such example of increased functionality is increasing the dynamic response time of fuel cells to be closer to that of a battery, which could be accomplished via in-situ storage of charge using storage materials as electrodes, or using the device to couple different electrochemical reactions. If a selected membrane material is coupled with the appropriate catalysts, hybrid fuel cell/battery devices become possible. For example, a SOFC with vanadium oxide electrodes can store charge for a short time in the electrode.³⁸ Alkaline fuel cells with MnO₂ and a metal hydride as electrodes can also both generate and store charge.^{39,40,41} Because electrochemical processes such as gas-phase diffusion, adsorption, and dissociation are not required when charge is already stored in an electrode, such devices could ramp to peak power, rather than operating on continuous power output as is done with state-of-the-art fuel cells. Integrating the functionality of fuel cells and batteries at the system level, one electrochemical device could incorporate the functionality of both, reducing the number of components in the overall system and therefore cost.

Another example of increased functionality in a fuel cell would be to use it for the electrochemical production of liquid fuels. The use of such a device would depend on its chemistry and location. One example would be for the device to be coupled to a variable renewable generator such as a wind turbine or solar panel. Excess electricity generated by the renewable resource could be used to electrochemically convert gaseous fuel such as methane to a liquid chemical to be stored in bulk. At a later time, this liquid fuel could be fed into a fuel cell (or other power generating device) in order to meet power demands. This example allows excess VER to be converted to a dispatchable energy resource. In another embodiment, a fuel cell could be located at a natural gas wellpad or digester, with the fuel cell providing power (electrical output) and also converting excess natural gas to a more easily transported, and higher value liquid chemical. In these examples, the electrochemical cell can be operated with electricity as an input or an output, depending on the electrochemical reactions coupled by the device. If the reaction is thermodynamically favorable, the device could potentially produce chemicals and electricity simultaneously.

Summary

The creation of novel, intermediate temperature fuel cell materials could not only lead to a decrease in the cost of fuel cells, but could enable a reinvention of fuel cell technology as a completely new, multi-functional device. These hybrid electrochemical systems, could, for example, include in-situ charge storage to enable a more dynamic response to

³⁵ J.R. Meacham, et al., *Journal of Power Sources* 156 (2006) 472-479.

³⁶ A.E. Auld, et al., *IEEE Transactions on Energy Conversion* 24 (2009) 617-625.

³⁷ F. Mueller, et al., *J. Power Sources* 187 (2009) 452-460.

³⁸ Q. Van Overmeer, et al., *Nano Lett.* 12 (2012) 3756-3760

³⁹ J. Hong, et al., *J. Power Sources*, 161 (2006) 753-760.

⁴⁰ C. Wang, et al., *J. Electrochem Soc.* 151 (2004) A260-A264.

⁴¹ D. Chartouni, et al., *Intl. J. Hydrogen Energy* 27 (2002) 945-952.

transients. Moreover, intermediate temperature operation opens up the use of never-before-possible, higher operating temperature hydrogen storage materials with high gravimetric storage densities. Magnesium hydride (MgH_2) for example, dehydrides at 300 °C and has a H_2 storage capacity of approximately 7.6 wt%.⁴² This and other materials with high capacities and higher dehydride temperatures are not compatible with the lower temperature operation of PEMFC, further underscoring the utility of intermediate temperature operation. In terms of fuel production, higher temperature devices such as SOFCs reform natural gas to H_2 and CO_2 gas using either a fuel processor and/or the anode itself. While lower temperature devices have little-to-no intrinsic fuel processing capability, at intermediate temperatures, there is the possibility to pursue chemistries other than complete oxidation of methane, such as partial oxidation and other reactions as discussed below.

C. PROGRAM OBJECTIVES

The overall objective of the REBELS program is to disrupt traditional learning curves for distributed stationary power generation, introducing technology concepts based on intermediate temperature fuel cells (ITFCs) that have the potential for significantly lower cost and are capable of performing outside the scope of current distributed generation technologies. The first specific objective of this FOA is to seek new solid electrolytes, electrocatalysts, fuel processing methods, and fuel cell manufacturing techniques to create ITFCs with high power density, a 10-year stack lifetime, and the potential to achieve an ultimate target for installed cost to the end-user of \$1,500/kW at moderate production volumes, and a nearer-term cost target of \$2,000-3,000/kW for niche commercial markets acting as early adopters. The second specific objective of this FOA is to expand the functionality of traditional fuel cells to benefit the stability of the grid and integration of renewable resources by creating either ITFCs that generate power and store charge in an electrode for battery-like response to transients, or hybrid systems capable of electrochemically converting methane or other gaseous hydrocarbons to liquid fuels.

D. TECHNICAL CATEGORIES OF INTEREST

This program is focused on supporting efficient, reliable, and fast-response ITFCs in one or more of the following three categories:

CATEGORY 1: ITFCs for DG applications

This category focuses on the creation of a 100 W short stack prototype that demonstrates high efficiency and reliability, as well as a pathway to lower cost via a combination of inexpensive materials and reduction of overall system components. The final performance metrics must be met with the use of a non hydrogen gas or liquid fuel. Projects in this category will focus on two of the three subsystems in an overall fuel cell system: the fuel processor and the fuel cell stack. The third subsystem, power electronics, is the focus of other ARPA-E programs such as Agile Delivery of Electrical Power Technology (ADEPT), and will not be a focus of this program.

Examples of potential research thrusts include, but are not limited to:

- Intermediate temperature solid state electrolytes with high ionic conductivity and stability
- High performance electrodes/electrocatalysts
- Novel concepts for activating C/H bonds beyond traditional steam methane reforming
- High-throughput methods of fabricating fuel cell stacks without high temperature sintering.

The ideal team in this Category will have relevant experience in multiple areas, rather than expertise in only one piece of the system (e.g. the electrolyte or the fuel processor).

CATEGORY 2: ITFCs with in-situ charge storage for dynamic response

This category focuses on fuel cells that also store charge in an electrode, enabling battery-like response to transient loads. For example an electrochemical cell consisting of a metal hydride anode, proton-conducting electrolyte, and cathode could operate either as a fuel cell or a rechargeable metal hydride/air battery. An intermediate operating temperature (200-500 °C) increases the number of potential anode materials, as there are many more materials available above 100 °C with hydrogen storage capacities > 7.5 wt%. Such a device could have a much faster response to transient

⁴² L. Schlapbach and A. Züttel, Nature 414 (2001) 353-358.

loads that are currently addressed by integrating fuel cells with either batteries or ultracapacitors. This new concept would integrate fuel cells and charge storage at the device-level rather than system-level, thus reducing the number of system components required for a given functionality. Similar functionality is envisioned for oxygen-based electrolytes with redox-active electrode species. **Note that these and all technology examples in this FOA are meant only to illustrate principles; they are *not* meant to prescribe or limit the technical approaches that might receive an award through the REBELS program.**

CATEGORY 3: ITFCs with fuel production capability

This category focuses on ITFCs that can also convert methane or other gaseous hydrocarbons to liquid fuels using excess renewable energy. Whereas high temperature operation typically results in reversible conversation of H₂ and O₂ to water or complete oxidation of CH₄ to H₂ and CO₂, intermediate temperatures could enable partial oxidation of CH₄ to CH₃OH or the formation of carbon-carbon bonds to make other liquid fuels or higher value chemicals. Examples could include conversion of methane or another hydrocarbon fuel to syngas, methanol, benzene, ethers, olefins, or other organics. The proposed choice of electrochemical half-reactions would determine whether electricity is an input or output in this device. Either would be acceptable for this category. This particular use of an electrochemical cell likens it to a small-scale gas-to-liquids reactor (GTL). The economics of GTL reactors were presented in the ARPA-E Reducing Emissions Using Methanotrophic Organisms for Transportation Energy (REMOTE) FOA.⁴³ Traditional GTL plants can only be built at large scale in order to achieve economic payback. These plants generally have a production capacity of >10⁴ barrels of oil equivalent per day (bpd), and high capital cost of the reactor per unit capacity, usually >\$100,000/bpd.⁴⁴ Electrochemical GTL has the potential to outperform these systems in cost, throughput, and efficiency while keeping the footprint of the reactor small. A competitive system would have lower cost per capacity, high process intensity, high selectivity, and long lifetime.

E. TECHNICAL PERFORMANCE TARGETS

Proposed technical plans must show a well-justified, realistic potential for the technology to meet or exceed the quantitative Technical Performance Targets described below. Prototypes developed under the work plan should credibly approach all the listed technical targets. In addition to the specific Technical Performance Targets, there are several categories that require the applicant to state a target value on their own.

CATEGORY 1: ITFCs for DG applications

End-of-project deliverables: (1) A short stack prototype of at least 100 W and consisting of at least 5 cells. The input fuel cannot be hydrogen. (2) A detailed cost model projecting system installed cost for early market adopters and at moderate production volumes.

ID	Category	Value
1.1	Desired operating temperature range	200-500 °C
1.2	Current density at 70% of Nernst voltage	> 200 mA/cm ²
1.3	Electrical efficiency at rated power	>50%
1.4	Startup time	< 10 minutes
1.5	Transient response	< 1 minute
1.6	Minimum stack testing time	1,000 hours
1.7	Power degradation rate	< 0.3% per 1,000 hours
1.8	Platinum group metal (PGM) total loading	< 0.1 mg PGM / cm ² electrode area

Supplemental Explanation of Category 1 Performance Targets

- 1.1 Fuel cells operating in the desired temperature range are strongly preferred, though ARPA-E may consider unique systems that operate at temperatures outside this range.
- 1.2 As measured on final short stack deliverable.
- 1.3 Ratio of DC output to net LHV of fuel.
- 1.4 Time required from cold start to rated power.

⁴³ <https://arpa-e-foa.energy.gov/FileContent.aspx?FileID=4f84a273-85d7-447c-9ffc-811282a97eb0>

⁴⁴ P. J. A. Tijm, *Gas to liquids, Fischer-Tropsch, Advanced Energy technology, Future's Pathway* (2010).

- 1.5 From 10% to 90% of rated power.
- 1.7 Degradation rate to be calculated using first polarization curve and a current density of at least 150 mA/cm² as a baseline. Degradation testing will include effects of steady-state operation as well as transient operation, startup, and shutdown.
- 1.8 Higher PGM content will be considered for selection if the application demonstrates an overall cost reduction (e.g. by elimination of an external reformer).

CATEGORY 2: ITFCs with in-situ charge storage for dynamic response

End-of-project deliverables: (1) An electrochemical cell prototype; unlike Category 1, the fuel may be hydrogen. The **same cell** must be capable of both fuel cell mode **and** battery mode operation but are not expected to run concurrently. (2) A high-level cost model projecting system installed cost for early market adopters and at moderate production volumes, to include the cost benefits of the in-situ charge storage.

ID	Category	Value
2.1	Desired operating temperature	200-500 °C
2.2	Current density at 70% of Nernst voltage	> 200 mA/cm ²
2.3	Minimum stack testing time	100 hours
2.4	PGM total loading	< 0.1 mg PGM / cm ² electrode area
2.5	Battery response time	< 1 second
2.6	Time at rated power	15 minutes
2.7	Battery cycling degradation	80% of loaded capacity retained after 30 cycles
2.8	Battery mode recharge time	< 1 hour
2.9	Self-discharge rate	< 5% of loaded capacity after 12 hours
2.10	Mode switching temperature	To be specified by the applicant

Supplemental Explanation of Category 2 Performance Targets

- 2.1 Fuel cells operating in the desired temperature range are strongly preferred, though ARPA-E may consider unique systems that operate at temperatures outside this range.
- 2.2 In fuel cell mode.
- 2.3 Continuous, steady-state operation in fuel cell mode.
- 2.4 Higher PGM content will be considered for selection if the application demonstrates an overall cost reduction (e.g. by elimination of an external reformer).
- 2.6 Length of time the cell can discharge in battery-mode at rated power.
- 2.10 Temperature change (if applicable) to enable battery mode from fuel cell mode.

CATEGORY 3: ITFCs with fuel production capability

End-of-project deliverables: (1) An electrochemical cell prototype; the input fuel must be methane or another gaseous hydrocarbon. Applicants may propose one electrochemical cell that operates in fuel cell mode and fuel production mode **or** one fuel cell and a separate electrochemical fuel production cell. (2) A high-level cost model projecting system installed cost for early market adopters and at moderate production volumes, to include the cost benefit of fuel production capability.

ID	Category	Value
3.1	Desired operating temperature	200-500 °C
3.2	Current density at 70% of Nernst voltage	> 200 mA/cm ²
3.3	Continuous cell operations	> 100 hours

3.4	Minimum cell area	> 100 cm ²
3.5	Current density (during fuel production)	> 100 mA/cm ²
3.6	Cell cost per rate of product output	< \$100,000/bpd
3.7	Process intensity	> 0.1 bpd/ft ³
3.8	Product yield	> 50 %
3.9	Carbon efficiency	> 50%
3.10	Desired product(s)	To be specified by applicant
3.11	Volumetric product output per cell	To be specified by applicant (L/day)

Supplemental Explanation of Category 3 Performance Targets

3.1 In fuel cell mode. Fuel cells operating in the desired temperature range are strongly preferred, though ARPA-E may consider unique systems that operate at temperatures outside this range.

3.2 In fuel cell mode.

3.3 Continuous, steady-state operation in fuel cell mode.

3.4 Minimum cell area for demonstration of liquid hydrocarbon production must be at least 100 cm² (roughly 4" × 4").

3.5 Minimum current density in liquid hydrocarbon production mode determines the maximum rate of product output, see

Table 4 (below) for sample calculations.

3.6 Cell cost per rate of product output defines the materials cost of the reactor per unit of production capacity of the reactor in \$/bpd, see

Table 4 (below) for sample calculations. For this calculation, reasonable assumptions must first be made to estimate a real cost for cell materials (\$/cm²) before the final cell cost per rate of product output.

3.7 Process intensity defines the volumetric size of the reactor system per unit production capacity. State-of-the-art large-scale GTL reactors (e.g. Shell-Pearl) have a process intensity on the order 0.02 bpd/ft³. To calculate process intensity for an electrochemical reactor, a unit cell thickness should be assumed and documented, see

Table 4 for sample calculations.

3.8 Product yield $Y_P (= X_R \cdot S_P)$ refers to the single-pass percentage product obtained from the reaction, and is calculated from the fraction of reactant converted per pass X_R and the selectivity for the desired products of the reaction S_P ; where,

$$X_R = \frac{m_{R,in} - m_{R,out}}{m_{R,out}}, S_R = \frac{m_{P,out}}{m_{R,in} - m_{R,out}}, m \text{ is mass and subscripts P and R are products and reactants, respectively.}$$

3.9 Carbon efficiency is calculated from $\eta_c = \frac{m_{C,Products}}{m_{C,Reactants}}$ where $m_{C,Products}$ and $m_{C,Reactants}$ are the mass of carbon in the

desired product and in the reactants, respectively. Applicants should provide a well-justified, realistic potential of achieving a carbon efficiency of greater than 50% for fuel production.

3.10 Desired liquid hydrocarbon product, the basic chemical reactions, and thermodynamics (free energy, enthalpy, and entropy) should be specified by the applicant.

Description	Symbol	Unit	Sample Products		
			pentane	benzene	methanol
Reaction			$5\text{CH}_4=\text{C}_5\text{H}_{12} + 4\text{H}_2$	$6\text{CH}_4=\text{C}_6\text{H}_6 + 9\text{H}_2$	$\text{CH}_4 + 0.5\text{O}_2 = \text{CH}_3\text{OH}$
Number of electrons	n	mol/mol	8	18	2
Faraday constant	F	C/mol	96485	96485	96485
Membrane active area	A	cm^2	100	100	100
Cell unit thickness*	ℓ	cm	1	1	1
Current density	j	A/cm^2	0.100	0.100	0.100
Molar mass product	M	g/mol	72.2	78.1	32.0
Density of product	ρ	g/mL	0.626	0.877	0.792
Enthalpy of combustion	$\Delta_c H^\ominus$	kJ/mol	3509	3273	715
Volumetric product output	$P_V = jAM/\rho nF$ ($\times 86400$)	mL/day	129	44	181
Areal product output	$P_A = j\Delta_c H^\ominus/nF$ ($\div 70.8$)	bpd/ cm^2	6.42E-06	2.66E-06	5.23E-06
Process intensity	$PI = j\Delta_c H^\ominus/nF\ell$ ($\times 400$)	bpd/ ft^3	0.18	0.08	0.15
Cell materials cost*	C_A	$\$/\text{cm}^2$	0.50	0.20	0.50
Cell cost per product output	C_A/P_A	$\$/\text{bpd}$	77,881	75,136	95,540

*Assumed

Barrel of oil equivalent (boe) = 6.12 GJ

Barrel of oil per day (bpd) = 70.8 kJ/s

3.11 Applicants should note assumptions and calculate the anticipated volumetric product output (mL/day) for a single, 200 cm^2 prototype cell.

Table 4: Sample calculations for Category 3

F. APPLICATIONS SPECIFICALLY NOT OF INTEREST

The following types of applications will be deemed nonresponsive and will not be reviewed or considered (see Section III.C.2 of the FOA):

- Applications that fall outside the technical parameters specified in Section I.E of the FOA
- Applications that were already submitted to pending ARPA-E FOAs.
- Applications that are not scientifically distinct from applications submitted to pending ARPA-E FOAs.

- Applications for basic research aimed at discovery and fundamental knowledge generation.
- Applications for large-scale demonstration projects of existing technologies.
- Applications for proposed technologies that represent incremental improvements to existing technologies.
- Applications for proposed technologies that are not based on sound scientific principles (e.g., violates a law of thermodynamics).
- Applications that do not address at least one of ARPA-E's Mission Areas (see Section I.A of the FOA).
- Applications for proposed technologies that are not transformational, as described in Section I.A of the FOA and as illustrated in Figure 1 in Section I.A of the FOA.
- Applications for proposed technologies that do not have the potential to become disruptive in nature, as described in Section I.A of the FOA. Technologies must be scalable such that they could be disruptive with sufficient technical progress (see Figure 1 in Section I.A of the FOA).

Applications that are not scientifically distinct from existing funded activities supported elsewhere, including within the Department of Energy.