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Short communication

Commercialization scenarios of polymer electrolyte membrane fuel cell applications for stationary power generation in the United States by the year 2015

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Abstract

Battelle is identifying the most likely markets and economic impacts of stationary polymer electrolyte membrane (PEM) fuel cells in the range of 1–250 kW in the U.S. by the year 2015. For this task, Battelle is using the Interactive Future Simulations (IFS^{TM}), an analytical modeling and forecasting tool that uses expert judgment, trend analysis, and cross-impact analysis methods to generate most likely future conditions for PEM fuel cell applications, market acceptance, commercial viability, and economic impacts. The cross-impact model contains 28 descriptors including commercial and technological advances in both polymer electrolyte membrane (PEM) fuel cells and fossil fuel technologies, sources of hydrogen, investments, public policy, environmental regulation, value to consumers, commercialization leadership, modes of generation, and the reliability and prices of grid electricity. One likely scenario to the year 2015 is that the PEM fuel cells will be limited to commercial and industrial customers in the range of 50–200 kW with a market size less than US$ 5 billion a year.

Keywords: Scenario analysis; Commercialization; Polymer electrolyte membrane fuel cells; Interactive Future Simulations; Stationary power generation

1. Introduction

While polymer electrolyte membrane (PEM) fuel cells are being deployed among electricity consumers, many uncertainties still remain to determine with confidence what commercialization strategies and investments in them today will lead to their substantial market penetration over the next 10 years or so. To manage these uncertainties, Battelle has undertaken for the U.S. Department of Energy an analysis of economic factors and commercialization conditions, including alternative futures (scenarios) of scenarios that capture likely future customers and needs for PEM fuel cells for stationary power generation in the U.S. to the year 2015. The scenarios were generated using Battelle's proprietary method and software program Interactive Future Simulations (IFS^{TM}), which has been applied for more than 55 scenario studies for government and industrial clients around the world. This paper presents scenarios generated based on information and expert judgment gathered in 2004 and are, of course, subject to change due to new information and revised judgments. The scenarios, therefore, should be viewed as a work in progress with potentially alternative futures emerging as new circumstances arise.

2. Background

2.1. Description of Battelle's scenario analysis method using Interactive Future Simulations (IFS^{TM})

The purpose of scenario analysis is to bind the uncertainties surrounding technological and commercial advances to frame reasonable expectations for products and services in the future. Scenarios are by definition conditional, so the

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alternative scenarios represent alternative outcomes of descriptors (trends, issues, and factors) by the target date. Rather than the better known intuitive approach, Battelle uses a cross-impact model that provides an analytical foundation for generating scenarios and provides computer-based simulations [1]. In the IFS^{TM} method, expert judgment is used to craft the topic question and to identify the descriptors that are most important to the topic question. The descriptors cover technological, economic, financial, marketing, regulatory, policy, and consumer behavioral issues and trends. Each descriptor is distinctly different and must have at least some interconnections with other descriptors. Each descriptor has two, three, or four likely alternative outcomes by the target year (2015). These alternative outcomes are mutually exclusive and exhaustive of all reasonable outcomes. They are typically expressed as ranges with the general bands of high, medium, and low relative to the definition of the descriptor. Each descriptor outcome is given an a priori, or initial or expert judgment, probability of occurrence according to Bayesian information theory. The sum of the a priori probabilities for each descriptor is 1.0. A cross-impact matrix is set up on the IFS computer software program and the cells of the matrix are filled, by expert judgment subject to peer review, by index values ranging from +3 to −3. The cross-impact values represent how the occurrence of one descriptor (and its alternative outcomes) would directly impact the occurrence of all other descriptors (and their alternative outcomes). The IFS algorithm calculates the adjusted probabilities and drives each descriptor outcome to 1.0 (occurs) or to 0 (does not occur) and generates clusters of coincident occurring descriptor outcomes (scenarios) [2].

2.2. Study methodology

For this specific project, the topic question was established in concurrence with the U.S. Department of Energy (DOE) as “What will be the most likely applications (and customers) and market sizes of stationary PEM fuel cells in the range of 1–250 kW in the U.S. by the year 2015?” Having established the topic question, Battelle conducted three expert focus groups from December 2003 to August 2004 to gather the judgments of various experts on the most important descriptors to be included in the scenario analysis. The first expert focus group provided a list of the most important issues from which the descriptors were derived. The second and third expert focus groups modified and expanded the list of descriptors to 28. They also reviewed and commented on all the inputs to the IFS^{TM} model.

The Battelle team, with the reviews and comments of government, industry, and academic experts, completed a cross-impact guide for each descriptor. The line of inquiry is whether or not and how each descriptor impacts all the other descriptors. This procedure provides the means of integrating all of the descriptors in net outcomes, or scenarios, of occurring and non-occurring outcomes for each descriptor (with scenarios having a posteriori probabilities of occurrence). The judgments made in the cross-impact analysis were shared and reviewed by the participants of the second and third expert focus groups and by additional Battelle colleagues not directly involved in the scenarios task.

3. Results

The IFS algorithm calculated 184 single scenarios, which clustered into five principal scenarios, which are as follows.

3.1. Scenario A: market disappointment

The most likely scenario (with a final probability of 47%) portrays a future in which both the technological and commercial developments of PEM fuel cells will most likely fail to achieve their ambitious goals. PEM fuel cell technology will progress beyond the state of the art of 2004, but the fuel cell product will prove to be a substantial disappointment to its champions and investors.

In this scenario, the retail prices for PEM fuel cells will be in the range of US$ 2000–3000 kW^{-1} capacity. It might also be in the lower range of US$ 1000–2000 kW^{-1}. (All prices appearing in this paper are expressed in constant 2004 dollars.) This price is less than today, but not as low as the objective of US$ 1100 kW^{-1}. The prevailing architecture of the PEM fuel cell will be the stack with controls and balance of plant, but it will have to be assembled with various peripherals required for specific applications, requiring professional (and potentially expensive) installation. The PEM fuel cell will have the market image as little more than an electric generator competing with other generators. In general, performance benefits will fail to meet customer expectations. PEM fuel cell operating costs, including fuels and maintenance, will be in the middle range of 10–20 cents kWh^{-1}.

There will be technological advances in PEM fuel cells, primarily in the areas of materials and controls, but PEM fuel cells will still require a hydrogen fuel of high purity that will most likely be centrally produced and packaged in canisters and tanks. The implication is that hydrogen will be seen as expensive relative to the commodity fuels of gasoline, diesel, methane, and methanol. In the meanwhile, advances in fossil fuel and internal combustion engine technologies will not progress much further than the state-of-the-art today. There will be marginal improvements in electric storage technologies. Fossil fuel prices will be in the range of one to two times base 2004 prices. Environmental regulations will require lower levels of emissions, but carbon management will be voluntary. In other words, the hydrocarbon-combustion energy paradigm will remain strong and competitive between now and the year 2015.

Public sector support of PEM fuel cells will be limited to specific tax breaks and research and development. The state and Federal governments will likely play a passive role relative to the primary leadership in the development and commercialization of PEM fuel cells by entrepreneurs, venture capitalists, and corporations. The national energy policy will emphasize free market dynamics and deregulation of the electric utility industry. Major gaps will remain between the evolving codes and standards for PEM fuel cells and the changing technologies and products on the market.

The country's general electric power grid will be characterized as basically sound but with reliability and quality inconsistencies (marked by periodic power failures and voltage irregularities). Grid electric prices will rise to a high level (in the range of 11–15 cents kWh^{-1} as an average of all customers across the U.S.). The structure of the U.S. electric industry will remain essentially as it is today. Distributed generation will be largely customer-driven, with an emphasis on customers buying and operating their own generators for backup power.

PEM fuel cells will be used primarily in isolated locales unconnected, underserved, or overpriced by the utility electric grid or in especially high-value applications (in which the failure of the grid would be seen as virtually catastrophic by customers). They will be seen as electric generators in competition with internal combustion engines or advanced batteries. The prevailing customers for PEM fuel cells will be commercial and light industrial. By implication, the prevailing size of PEM fuel cells in this market will be in the middle range of about 50–200 kW capacity. The most likely market for PEM fuel cells in the U.S. by the year 2015 will be less than US$ 5 billion sales per year for stationary power generation. PEM fuel cells as viable products will generally be disappointing for both product producers and users relative to expectations that exceed experience.

3.2. Scenario B: qualified success in residential and light commercial applications

The second scenario, which has a probability of 33%, portrays a more optimistic future for PEM fuel cells than provided by Scenario A. In Scenario B, PEM retail prices, unit architecture, and operating costs are the same as in Scenario A, but installation will be characterized as easy ("plug-and-play") or relatively easy by local contractors and performance benefits will consistently meet customer expectations. PEM fuel cell technology advances will be substantial, reflecting system-wide innovation and optimization. The stack will be designed to optimize the use of hydrogen or a hydrogen-rich fuel without the need for an additional fuel processor. PEM fuel cells will primarily use hydrogen or hydrogen-rich commodity fuels. By implication, the hydrogen infrastructure will be in place to support PEM fuel cell commercialization. The hydrogen might be high quality (purity) in a form that is relatively easy to store and transport, or the hydrogen might be in the form of methanol or a similarly hydrogen-rich fuel, mostly likely in a liquid form. The public policy in support of PEM fuel cell development and commercialization will be characterized as providing numerous subsidies, credits, tax breaks, and other types of financial incentives offered by both the Federal and state governments. The national energy policy will be driven primarily by concerns of national security and homeland defense. Codes and standards for PEM fuel cells will exist, but they will be not be comprehensive and only partially aligned with changing technologies and fuel cell products. The national electric grid will be highly reliable, with only occasional exceptions. Large power failures will be relatively brief and localized. Grid electricity prices will be in the medium level of 7–10 cents kWh^{-1} as a national average across all customers. Distributed generation will grow as a cooperative and combined effort of customers and electric utilities. In this context, PEM fuel cells will increase in popularity as energy efficient and environmentally friends power generators for both backup and peak-shaving applications. They will compete well with advanced internal combustion engines and renewable energy forms. The prevailing customers for PEM fuel cells will be residential and light commercial. Residential customers might include a broad range of private residences, including individual homes, neighborhoods or subdivisions, apartment and condominium complexes, and gated communities. By implication the prevailing PEM fuel cell unit successful in the marketplace will be of relatively small sizes, less than 50 kW capacity. The market size for PEM fuel cells will be in the medium range of US$ 5–8 billion sales per year by the year 2015. By this time, PEM fuel cells will be seen as a qualified commercial success — products will be produced and sold and customers will be happy, but the market sales will not be as high as expected by avid product champions and investors.

3.3. Scenario C: roaring success

The third scenario, which has a probability of 12%, is virtually the opposite of Scenario A. In this scenario, both the technological developments and the market commercialization meet high expectations for producers, customers, and investors. PEM fuel cell product prices will be in the range of US$ 2000–3000 kW^{-1} capacity. The architecture will be a fully integrated unit requiring no further modifications or adaptations for customers. Installation will be easy and inexpensive (plug-and-play). Technological advances will be substantial with system-wide innovation and optimization. The unit will include fuel management allowing for the use of hydrogen or hydrogen-rich fuels without an additional fuel processor. Operating costs will be in the middle range of 10–20 cents kWh^{-1}.

As in Scenario B, PEM fuel cell performance benefits will consistently meet customers' expectations, and it will enjoy the market image of a high-tech and -gloss product. PEM fuel cell investments will be in the high range of more than US$ 2 billion a year by 2015. PEM fuel cells will be mass-produced with high quality control and high volumes, greatly improving performance quality while reducing costs. Also as in Scenario B, the principal fuel source will be hydrogen or hydrogen-rich commodity fuels with an infrastructure adequate to support the extensive commercialization of fuel cells. But unlike Scenario B, the public sector will become a lead buyer and customer of fuel cells. National energy policy will stress both energy sufficiency and national security. Codes and standards will be comprehensive and fully aligned with changing fuel cell technologies and products.

The national electric grid, the same as in Scenario B, will be highly reliable, but with occasional exceptions and grid prices will be in the high range of 11–15 cents kWh^{-1} across the country and across all customers. Distributed generation will be a combined and cooperative endeavor of customers and electric utilities. In this scenario, unlike Scenario B, fuel cells will be used for more than just distributed generation, they will be used on a continuous basis for premium power with great flexibility for backup, peak shaving, and optimal electric load management synchronized with the electric grid. The prevailing applications and customers for PEM fuel cells will be residential and light commercial (with units of less than 50 kW capacity) and the market size will be in the high range of more than US$ 8 billion in sales per year by 2015.

3.4. Scenario D: success with a hydrocarbon infrastructure

The fourth scenario, which has a frequency of 5%, is very similar to Scenario C, but with one major difference: the fuels for PEM fuel cells will be hydrocarbons requiring an additional fuel processor (including fuel reformer). The PEM fuel cell can experience a high level of commercial success even within the current structure of the hydrocarbon (oil, gasoline, diesel, and natural gas/methane) infrastructure. Also in this scenario, retail prices must be low, less than US$ 1000 kW^{-1}capacity. Another way to say this is that fuel cell unit prices might be higher with a hydrogen infrastructure than with a hydrocarbon infrastructure. One obvious reason is that in Scenario D, the customer will have to buy and install a fuel processor in addition to the fuel cell unit. In all other aspects, Scenario D is identical with Scenario C. It should be remembered that the probability of Scenario D is less than half of the probability of Scenario C, suggesting that commercial success of the PEM fuel cell depends more upon commodity hydrocarbon or hydrocarbon-rich fuels than on lowest PEM fuel cell unit prices.

3.5. Scenario E: qualified success in commercial and light industrial applications

The fifth scenario, which has a probability of just 3%, is similar in many ways to Scenario B. In both Scenarios B and E, the market size will be in the middle range of US$ 5–8 billion a year by 2015. The difference, however, is that in Scenario B, the principal applications and customers will be residential and light commercial, whereas in Scenario E, they will be commercial and light industrial (with units in the range of 50–200 kW capacity). In Scenario E, retail prices will be in the range of US$ 1000–2000 kW^{-1} capacity. Installation will be achieved with the use of local contractors (with virtually no plug-and-play options). Unlike Scenario B, the market image of a PEM fuel cell will be that of an effective electrical generator and heat appliance (but not that of the high-tech and -gloss consumer product). Also, electric grid prices will be in the high range of 11–15 cents kWh^{-1} averaged across the country and across all customers.

4. Discussion

The results of scenario analysis, as performed by cross-impact analysis and the IFS^{TM} software program, can be read in at least two different ways. One form of analysis, as shown above, is to look at the rank order of most likely scenarios (as determined by a posteriori probabilities and scenario type clustering). Another way, however, is to look at the scenario that is most desired, regardless of how likely is may be, and determine what conditions (descriptors outcomes) would have to occur in order to achieve desired results.

In this study, from the perspective of market penetration and sales, the most desirable scenarios would be Scenario C, roaring success, and Scenario D, success with a hydrocarbon infrastructure, both of which contained a PEM fuel cell market size in the high range exceeding US$ 8 billion annual sales by 2015. Understanding the differences between Scenarios C and D and Scenario A, market disappointment, leads to an understanding of what conditions will likely lead to commercial success as opposed to failure. Also, the differences between Scenarios C and D with Scenarios B and E show the differences between high and medium levels of market success. The key elements of success – what differentiates winning from losing in PEM fuel cell commercialization – are as follows: (1) unit prices will most likely be in the US$ 2000–3000 kW^{-1} range, except in the scenario of success with the hydrocarbon infrastructure, in which they must be in the low range of less than US$ 1000 kW^{-1}. With hydrocarbon or hydrocarbon-rich commodity fuels and with a fully integrated unit with the capacity for plug-and-play installation, a PEM fuel cell can be successful in the lower, but not lowest, price range of US$ 2000–3000 kW^{-1} capacity, (2) the PEM fuel cell architecture must be fully integrated, including within one unit the stack, controls, power electronics, balance of plant, internal fuel handling, and all peripherals, (3) the market image must be high-tech and -gloss, “best thing since sliced bread.” The positioning of an electric generator, even with ancillary heat, is boring to the broader consumer rather than the narrower technical circle of buyers, (4) customer benefits and expectations must be consistently met, (5) technical advances must be substantial and achieve system-wide innovation and optimization (parallel with integrated architecture), (6) hydrogen or hydrogen-rich fuels must be widely available and priced like commodities. This may require a hydrogen infrastructure, although other possibilities are emerging, (7) codes and standards must be updated continually and they must be comprehensive and aligned well with changing PEM fuel cell technologies and products, (8) government support must be substantial, including being a lead buyer and customer of PEM fuel cells, (9) national energy policy must emphasize both energy sufficiency and security, (10) distributed generation must be a combined and cooperative endeavor of both electricity consumers and electric utilities, (11) electric grid prices must be in the high range of 11–15 cents kWh averaged across the U.S. and across different types of customers, (12) PEM fuel cells must be able to run continually or continuously as generators of premium power for base, backup, and peak-shaving loads in cooperation with the electric grid, (13) PEM fuel cell operating costs must be in the middle range of 10–20 cents kWh^{-1}, and (14) to achieve the high range of sales, the PEM fuel cell must be attractive to residential and light commercial customers. This suggests a unit size of less than 50 kW capacity. It is easy to interpolate that the initial success may be in the isolated, high-value applications with progression toward large commercial and office building applications (most likely in the 50–200 kW capacity sizes). The analysis does support the conclusion that if the PEM fuel cell cannot progress toward the residential and light commercial market, it will not likely go beyond the middle level market size.

Battelle plans to conduct further trends research in support of the scenarios. Further sensitivity analysis and the simulation of disruptive events will be performed with the IFS software program. As new information becomes available and as new events occur, revisions will be made to the scenario inputs that will like change the scenario results.

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