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Development of a Novel Technological Readiness Assessment Tool for Fuel Cell Technology

SLOBODAN PETROVIC AND EKLAS HOSSAIN, (Senior Member, IEEE)
Oregon Renewable Energy Center (OREC), Department of Electrical Engineering and Renewable Energy, Oregon Institute of Technology, Wilsvonville, OR 97601, USA

Corresponding author: Slobodan Petrovic (slobodan.petrovic@oit.edu)

ABSTRACT Technology Readiness Level and Manufacturing Readiness Level evaluation methodologies have been applied for a long time by the aerospace and defense industries to systematically determine the state of readiness for their products and processes. These tools have been proven to be extremely valuable not only in assessing the stages of product development, but also in providing requirements and guidance for continuing pursuit towards final products. This paper describes the creation of a novel and unique technology readiness level methodology tool that applies specifically to fuel cell technologies. This evaluation tool used modified criteria from the above-mentioned readiness level tools and adapted them to reflect the aspects of fuel cell technology. The biggest challenge in developing the readiness evaluation tool was due to the fact that there are several different fuel cell types and many different applications. In this complex matrix of drastically different conditions and diverse components, a general evaluation tool was developed first. Subsequently, specific versions of the tool will be developed to reflect the fuel cell types and applications. The Fuel Cell Technology Readiness Level (FCTRL) methodology is developed for those skilled in the art of fuel cells, engineers, and other professionals who need to evaluate fuel cell technologies for integration into existing systems and applications, as well as for anyone interested in fuel cells and renewable energy systems in general. The tool can also be very effective for use by investors planning to fund a fuel cell projects or government panels in charge of assigning research funds. The FCTRL evaluation tool comprises seven levels and a varying number of specific criteria within each level. The application of the tool is relatively simple in the form of a checklist. The technology is assumed to progress to a higher level once all criteria in the lower level are met. An example of the application is presented for a general case of fuel cell technology and places the most advanced fuel cell product in the correct level of readiness. The FCTRL is expected to make a significant impact on understanding fuel cell technology and its role in the energy systems poised to replace conventional energy technologies.

INDEX TERMS Fuel cell, energy storage, battery, technology readiness level, manufacturing, commercialization, risk assessment.

NOMENCLATURE

AFC:	Alkaline Fuel Cell
BMRL:	Business and Market Readiness Level
CHP:	Combined Heat and Power
DMFC:	Direct Methanol Fuel Cell
DOD:	Department of Defense
DOE:	Department of Energy
FC:	Fuel Cell
FCTRL:	Fuel Cell Technology Readiness Level
FRP:	Full Rate Production
KPP:	Key Performance Parameters
LPG:	Light Propane Gas
MCFC:	Molten Carbonate Fuel Cell
MEA:	Membrane Electrode Assembly
MMP:	Manufacturing Maturation Plan
MRA:	Manufacturing Readiness Assessment
MRL:	Manufacturing Readiness Level
NASA:	National Aeronautics and Space Administration
PAFC:	Phosphoric Acid Fuel Cell
PBI:	Polybenzimidazole
PEMFC:	Proton Exchange Membrane Fuel Cell

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QA: Quality Assurance
R&D: Research and Development
SOFC: Solid Oxide Fuel Cell
TRL: Technology Readiness Level

I. INTRODUCTION

Fuel cells are one of the best examples of the slow exploitation of a promising technological development. Throughout their long history, fuel cells have emerged numerous times into the forefront of the movement for improving the way chemical energy is converted into electricity. These technological periods in which fuel cells were considered attractive always coincided with the periods of increased environmental concerns related to global warming and the need to reduce CO_2 emissions or with the periods of alarming trends in fossil fuel availability and pricing. During those periods, fuel cell technology would be pushed into a spotlight and proclaimed as the universal solution for the energy crisis and environmental protection. The excitement with fuel cells resulted each time in expanded interest and more investments, which in turn led to the creation and growth of businesses and various other organizations dedicated to fuel cell technology development. Along with this, the population of those in the scientific and engineering community involved in fuel cells grew as well.

Throughout the past century, fuel cells have gradually shaped up to the form as we know them today. It is not possible to condense the entire development history within the limits of one paper, though a reflection of concurrent works can be made to demonstrate the research progress made so far in this promising field. Several works have been dedicated to creating a comprehensive review of fuel cell technologies, including the basic principle, detailed classification, challenges, advantages and disadvantages of fuel cells [1]–[7]. In addition to these, the power electronic devices used along with fuel cells have been highlighted in some works [8], [9]. The concept of fuel cells is so vast and immensely intriguing that numerous books and chapters have been devoted to the discussion of fuel cell technology [10]–[13]. One of the major reasons fuel cells have not yet been brought to historically expected levels of readiness for commercialization is the lack of standardized manufacturing processes and evaluation tools. Fuel cells are still produced using largely manual methods, very specific to each developer and that lack of consistent vision has certainly contributed to the failure to deliver practical, commercial products. Additionally, the inability of researchers to solve some fundamental problems and the lack of coherent marketing strategy and determination to force the progress, makes the estimates of fuel cell readiness extremely difficult.

Therefore, the goal of this paper is to use some known evaluation tools, applied typically in projects of critical importance and high-volume manufacturing operations, to appraise the present status of fuel cell technology and offer recommendations for the next development period. The analysis of manufacturing and commercialization risks will critically examine all aspects of fuel cell technology and the results will present a realistic assessment of the remaining challenges.

The rest of the paper is organized as follows: Section II provides the background of fuel cells, including their history, operating principle, and detailed classification. Section III contains an elaborate discussion on technological readiness levels (TRL), manufacturing readiness levels (MRL) and business & market readiness levels (BMRL). These three existing tools have been utilized to define the proposed fuel cell technology readiness levels (FCTRL). Section IV describes the current status of fuel cell technology, based on concurrent works and technical targets, and highlights application areas of fuel cells. Section V further describes fuel cell technological readiness levels, as well as the development of appropriate tools, which is the main topic of this work. Section VI provides a general assessment of fuel cell technology based on the developed FCTRL tool. Finally, Section VII concludes the paper.

II. BACKGROUND OF FUEL CELLS

Understanding the level of progress fuel cells have made throughout their relatively long history is one of the keys in assessing not only the technology readiness level, but also the risks and future prospects. From the very early pioneering days of this invention, experiments were focused on achieving the promise of high theoretical efficiency. These efforts were primarily aimed at improving the materials and designs for main fuel cell components: electrodes, electrolyte, and housing. It will become evident from the subsequent discussions that there are very minor fundamental differences between the early electrode and catalyst materials and those currently used in modern fuel cells. The first catalytic material to be used was platinum and it is still used at this time. Even the mechanistic explanations of the reactions do not significantly differ from the very first reported fuel cell to present time. The electrolyte materials, on the other hand, have changed dramatically and instead of one, there are now five major electrolyte types. As a matter of fact, fuel cells are now classified based on the electrolyte and closely associated temperature of operation. Because of this diversification, each fuel cell type can be closely considered a different or distinctive device.

The concept of fuel cells was discovered in 1839 by William Robert Grove, who at that time described it as a ‘‘gaseous voltaic battery’’, analogous to previously known batteries [1]. As explained in the next section, fuel cells require two electrodes (anode and cathode) and an electrolyte. In the original Grove's experiment, the cell was made of two platinum electrodes immersed in sulfuric acid. The hydrogen and oxygen gases were supplied from the inverted tubes encapsulating the electrodes. The reaction took place in the thin electrolyte film left after the displacement of electrolyte by the reactant gases when the tubes and electrodes were immersed into the electrolyte.

The interest in this new device continued at a slow pace until the end of the 19th century. During the time when practical attempts to build internal combustion engines were flourishing, the gaseous voltaic battery remained relatively unexplored. Still, inspired by Grove's experiments, Lord Rayleigh made improvements in the platinum electrode design from a piece of wire to a sponge electrode capable of increasing the surface area for the reaction [14]. Mond and Langer introduced a diaphragm to contain the difficult-to-handle liquid electrolyte, and by doing so managed to build the first fuel cell prototype as a self-contained device [15].

Around the turn of the century, four types of fuel cell were known based on the electrolyte material: acid, alkaline, carbonate, and oxide. Fuel cells based on phosphoric acid, instead of sulfuric acid, were developed for utility companies in the 1960s and 1970s. In the same time period, a new type of electrolyte based on thin polymer films with incorporated acid was discovered and used in the Gemini space program. Space programs were historically the biggest impetus for fuel cells and the reason they came out of relative obscurity. The next fuel cell used in the Apollo missions was based on an alkaline electrolyte. It was originally developed by Francis Bacon [16] and improved by Pratt & Whitney Aircraft [17].

Based on the original work by Walther Nernst, another type of fuel cell was developed that was based on solid oxide ion conductors and named solid oxide fuel cell [18]. This is a high-temperature fuel cell operating at over 800°C. The concept was further improved over time and culminated in the 1960s when Westinghouse Electric Corporation demonstrated a solid oxide fuel cell using a tubular design and zirconium oxide solid electrolyte. The fuel cell used natural gas as a fuel [19]. A molten carbonate fuel cell was developed as a method for direct conversion of coal to electricity. This type of fuel cell uses a mixture of alkali metal carbonates as the electrolyte and operates at temperatures above 600°C. Through improvements of some earlier experiments, Davtyan [12] constructed a fuel cell using a mixture of molten and solid phases, while General Electric Company [11] further optimized the design of electrodes and electrolyte matrix.

Currently, all types of fuel cells are at different stages of use and development. At the moment, the most popular type is undoubtedly the proton exchange membrane (PEM) or the solid polymer electrolyte (SPE) fuel cell, which is based on ion-conducting polymer films. This type is so widely used that it held a market share of 90.7% in 2018. With this in mind, the risk assessment analysis will be mostly applied to this type of fuel cell. Nonetheless, it becomes more obvious from this brief overview of fuel cell history that diversification of fuel cell technology based primarily on the electrolyte type and temperature of operation, or the fuel used, has potentially contributed to the dispersion of efforts, slow fuel cell development, and modest commercial presence.

The basic principle of operation of a fuel cell involves the oxidation of fuel (usually hydrogen) on the anode to produce protons and electrons. The protons are then transported through the electrolyte to the cathode side, while the electrons flow through an external circuit, producing electrical power and powering a load. On the cathode, oxygen, protons, and electrons react to form water. A single fuel cell produces a theoretical output voltage of only 1.23V at room temperature and multiple cells are stacked together in series to obtain a higher voltage or in parallel for higher current. The principles of operation of fuel cells differ from other devices that utilize fuel because the oxidation and reduction sites are physically separated by the electrolyte. This offers great opportunities for precise control of the reaction, but also poses some challenges. Figure 1 shows a diagram of a fuel cell. The electrochemical reactions that take place in a fuel cell with acidic electrolyte are as follows:

$$\text{Cathode}: O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$
$$\text{Anode}: 2H_2 \rightarrow 4H^+ + 4e^-$$
$$\text{Overall}: 2H_2 + O_2 \rightarrow 2H_2O$$

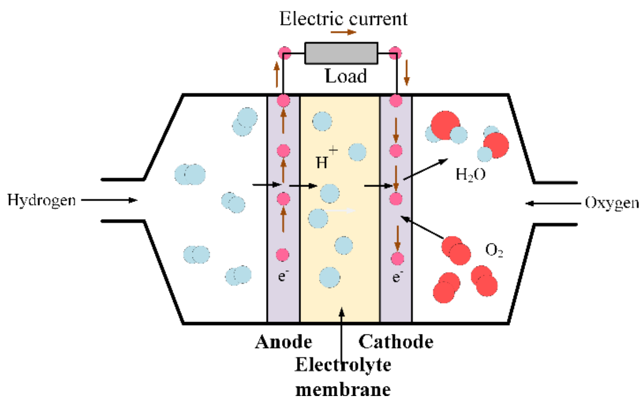

FIGURE 1. Schematic representation of the operation of a fuel cell. The primary choice of fuel is hydrogen, which releases H^+ and e^- on the anode side. The electrons travel through an external circuit to produce electric current. The H^+ and e^- react on the cathode side with oxygen to produce water.

Fuel cells are categorized as electrochemical devices similar to batteries, with the major difference being that they can operate, producing power, as long as there is a fuel supply. The simplest and ideal fuel cell is the one that uses hydrogen as fuel. If hydrogen is used, the only products of the fuel cell reaction are electricity and pure water. As a result, they are environmentally friendly because they produce no harmful emissions, only water and a small amount of heat. Fuel cells convert the chemical energy of a fuel directly to electricity and are not subject to Carnot thermal engine efficiency laws. At low temperatures, they are much more efficient (about 50-60%) than other methods of generating electric energy. They are ideal as energy storage devices because they have high energy density when hydrogen is used. Fuel cells can be used in several electrical grid applications, such as load levelling, peak shaving, demand side management, and others. They have no moving parts and are noise-free. As a result of these numerous advantages, fuel cell technology is well positioned for widespread commercial use in three main application areas: transportation, stationary power, and portable devices. These applications require different conditions and performance for the fuel cell devices. Consequently,

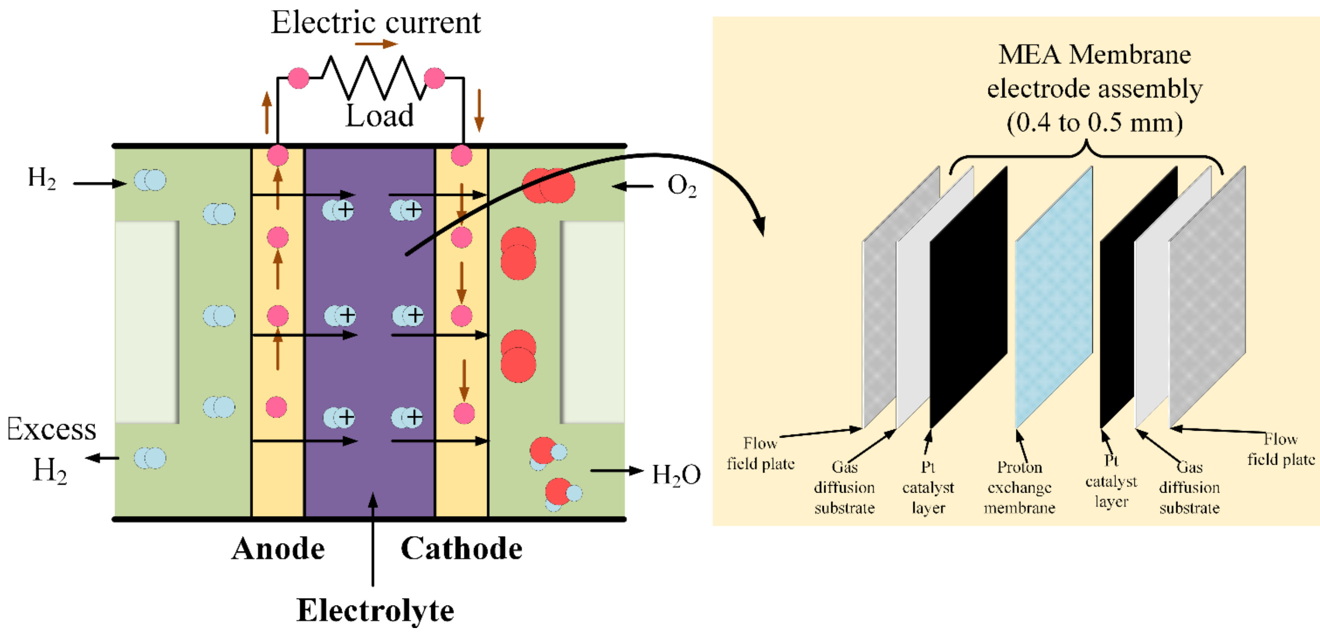

FIGURE 2. Illustration of a PEMFC. The proton exchange membrane is permeable to cations, but impermeable to electrons. The PEMFC comprises a membrane electrode assembly, as shown in the magnified section.

fuel cells for each application will be evaluated separately for manufacturing risks.

Besides different application requirements, complexity is increased due to the range of fuel cell types, each with a characteristic electrolyte and temperature of operation. Sometimes, classification is also made based on the fuel used. Using the type of electrolyte as classification, there are five fuel cell types: Proton Exchange Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cell (PAFC), Alkaline Fuel Cell (AFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC). These are briefly discussed here, along with a short description of a fuel cell based on the fuel used - Direct Methanol Fuel Cell (DMFC).

A. PROTON EXCHANGE MEMBRANE FUEL CELL (PEMFC)

The proton exchange membrane fuel cell (PEMFC) uses thin polymer films as electrolyte and operates at 50-100°C. The basic construction blocks are called membrane-electrode assemblies (MEAs) and consist of a thin polymer membrane sandwiched between two electrodes containing catalysts (commonly platinum) and additional layers to provide effective reactant gas supply and electron removal. A very intimate contact is required between the membrane and the catalyst, which is typically achieved by applying thin, liquid membrane coatings, called ionophores that protrude from the membrane film and into the catalytic electrode. The MEAs are placed between the collector plates (i.e., flow-field plates) that contain gas distribution channels. This is the most commonly used type of fuel cell because of the relatively simple construction and highest power densities of all fuel cells. The biggest challenges for this technology are membrane performance dependence on the presence of water and the resulting need for reliable humidification of gases, as well as the high cost of the platinum catalyst. An additional problem with these fuel cells is that they require very pure hydrogen. The PEMFCs will be discussed in more detail in the next section since they are the main candidates for commercial use in all three application areas. Basic fuel cell reactions are applicable for PEMFC. Figure 2 shows the construction and operation of a PEMFC.

B. ALKALINE FUEL CELL (AFC)

Alkaline fuel cells (AFC) are one of the oldest fuel cell types with an impressive history of performance in space programs. This type of fuel cell uses an aqueous alkaline electrolyte (typically KOH) and operates in the temperature range from 60-120°C. In an aqueous solution, KOH dissociates into K^+ and OH^- ions. Hydrogen is oxidized on the anode and forms water in the reaction with the OH^- ions. The electrons flow through the external circuit, powering the load. On the cathode, oxygen reacts with water and electrons to form OH^- ions. Consequently, the electrolyte is not consumed in the reaction. The diagram of an AFC is shown in Figure 3. The reactions in the alkaline medium are given below.

$$\text{Anode}: H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$$
$$\text{Cathode}: O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$
$$\text{Overall}: 2H_2 + O_2 \rightarrow 2H_2O$$

AFCs are characterized by their quick starting capability. They also have a very high efficiency of around 70%. The biggest disadvantage of AFCs is the absorption of CO_2 from air, which results in the formation of carbonates and the reduction of electrolyte conductivity. The use of AFC

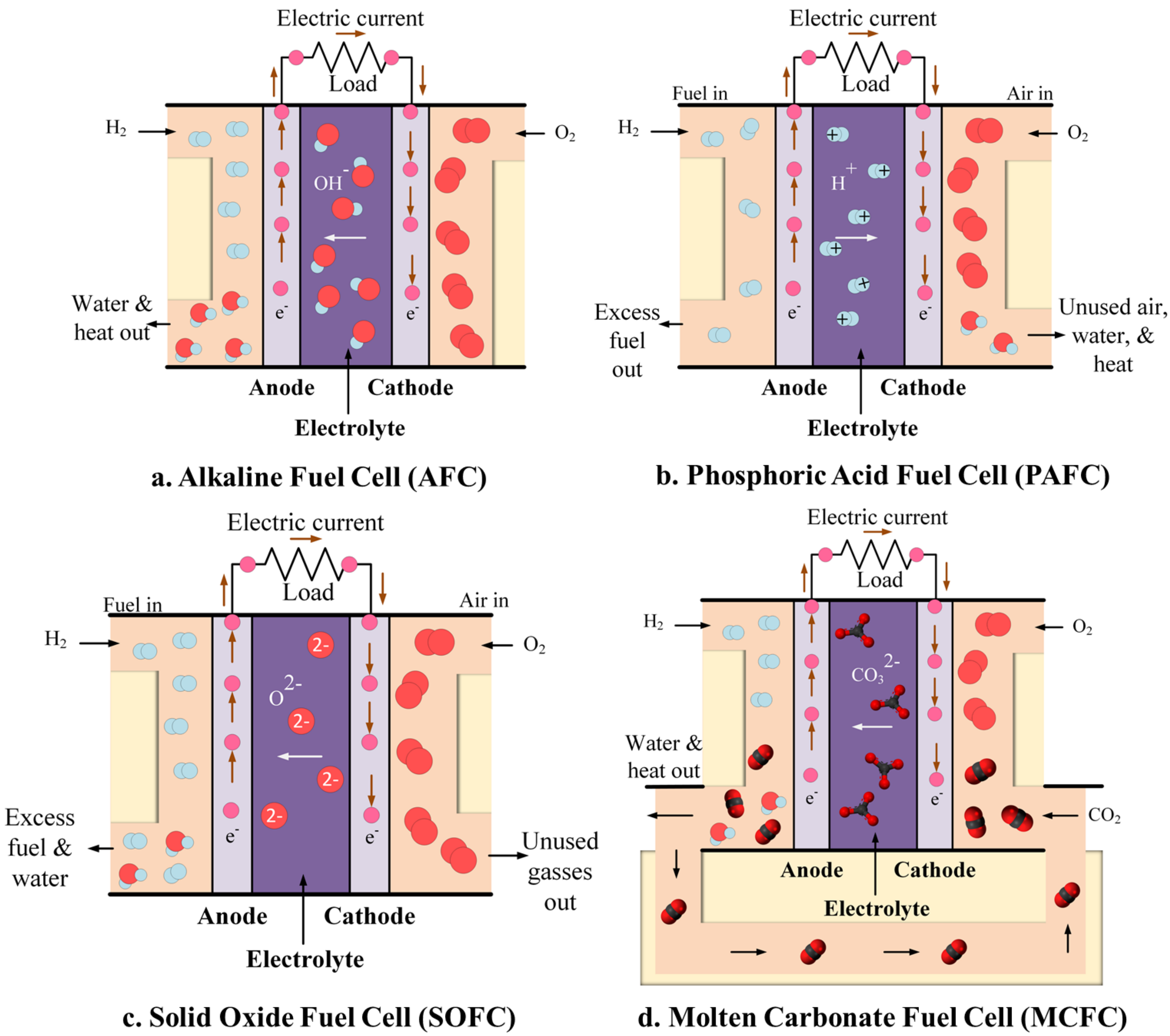

FIGURE 3. **Schematics of a) Alkaline Fuel Cell (AFC), b) Phosphoric Acid Fuel Cell (PAFC), c) Solid Oxide Fuel Cell (SOFC) and d) Molten Carbonate Fuel Cell (MCFC). These fuel cells vary in the type of electrolyte and electrode reactions (while the overall reactions are the same).**

is, therefore, limited to short term applications (such as in the space shuttle) or restricted by the need for recirculating electrolyte.

C. PHOSPHORIC ACID FUEL CELL (PAFC)

Phosphoric acid fuel cells (PAFC) use phosphoric acid as electrolyte and operate at temperatures from 180 – 210°C. Because of the higher temperature of operation than PEMFC and AFC, PAFCs can tolerate hydrogen fuel with a small percentage of carbon monoxide, which for some applications can be a great advantage. A platinum catalyst is required for PAFC, making it quite expensive. Of all fuel cell types, this technology has produced the most working units and showed great promise for stationary applications in the 1970s. The biggest disadvantages of phosphoric acid fuel cells are their comparatively low current density and the public perception of hazard due to the use of strong acid. These are the main reasons they have been nearly abandoned at this time, although there are some recent designs that use phosphoric acid electrolyte embedded in solid polymer membrane films. Basic fuel cell reactions in acidic electrolyte are applicable for PAFC.

D. SOLID OXIDE FUEL CELL (SOFC)

Solid oxide fuel cells (SOFC) function by using solid oxide or ceramic electrolytes that transport O^{-2} ions, for example, zirconium oxides. Their temperature of operation is above 800°C. At such a high temperature, oxygen is reduced to oxygen ions at the cathode, which then diffuse through the solid oxide electrolyte towards the anode and react to oxidize the fuel. The hydrogen does not need to be pure and even other hydrocarbons such as natural gas can be used. SOFCs are characterized by fast reaction rates and are considered cost effective fuel cells. The electrode reactions and the overall cell reaction are as follows:

$$\text{Cathode}: \frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$$
$$\text{Anode}: H_2 + O^{2-} \rightarrow H_2O + 2e^-$$
$$\text{Overall}: H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

E. MOLTEN CARBONATE FUEL CELL (MCFC)

Molten carbonate fuel cells (MCFC) typically operate at around 650°C and use molten sodium and potassium carbonates as electrolyte. MCFCs can use fuels other than pure hydrogen, such as natural gas, which is converted into pure hydrogen by a process called internal reforming. MCFCs do not require an expensive catalyst nor pure hydrogen and, as a result, are more cost-efficient than other fuel cells. They are, however, not completely emission-free if fuels other than pure hydrogen are used because of the carbon dioxide generation. These fuel cells are characterized by high efficiency, especially if the waste heat can be utilized. The reactions occurring in MCFCs are shown below.

$$\text{InternalReformer}: CH_4 + H_2O \rightarrow 3H_2 + CO$$
$$\text{Anode}: H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$$
$$\text{Cathode}: CO_2 + \frac{1}{2}O_2 + 2e^- \rightarrow CO_3^{2-}$$
$$\text{Overall}: H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

Figure 3 compares AFC, PAFC, SOFC and MCFC: their working procedures, type of electrolyte used, and internal reactions.

F. DIRECT METHANOL FUEL CELL (DMFC)

While SOFC and MCFC are mainly competing for the stationary electricity generation market, the best candidate for portable applications is the direct methanol fuel cell (DMFC). The name for the technology in this case comes from the type of fuel used (i.e. methanol) rather than the electrolyte as in the fuel cell types described above. In principle, DMFC could use different electrolytes, but the most common one is a polymer electrolyte membrane similar to one used with hydrogen as a fuel.

The biggest problems with DMFCs are in the need for a special methanol oxidation catalyst and methanol crossover from anode to cathode resulting in a drastic reduction in performance. Figure 4 shows the schematic diagram of a DMFC. The reactions that take place inside a DMFC are as follows:

$$\text{Anode}: CH_3OH + H_2O \rightarrow 6H^+ + 6e^- + CO_2$$

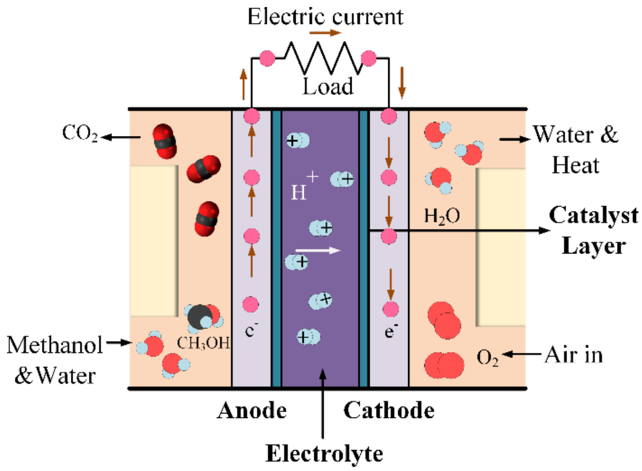

FIGURE 4. Schematic representation of Direct Methanol Fuel Cell (DMFC). This fuel cell uses methanol as fuel.

$$\text{Cathode}: \frac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$$
$$\text{Overall}: CH_3OH + \frac{3}{2}O_2 \rightarrow 2H_2O + CO_2$$

III. TOOLS FOR EVALUATING READINESS

The three risk assessment tools: Technology Readiness Levels (TRL), Manufacturing Readiness Level (MRL), and Business and Market Readiness Level (BMRL) have been adapted from the aerospace and semiconductor industries. These tools have proven invaluable in estimating the risks for many successful programs and have provided a critical dimension of understanding and planning for these two winning industries, which have arguably achieved the most triumphant technological endeavors in modern history. The combination of these three tools is fully appropriate for evaluating such a complex and diverse technology as fuel cells and providing guidelines for future fuel cell directions and investments.

A. TECHNOLOGY READINESS LEVEL (TRL)

Technology Readiness Levels (TRLs) [20], [21] were originally developed by NASA as a systematic measurement system that supports the assessment of the maturity of a particular technology. The system also enables comparison between different types of technology. The TRL evaluation system consists of nine levels used to determine the maturity of the technology. The nine levels are shown in Figure 5.

Levels 1-3 describe initial technology development, usually in an academic setting, first by observing the scientific principles, then identifying possible target applications, followed by completing the feasibility studies. The fourth level looks at concept refinement and initial device fabrication. At level five, the technology is further developed and tested under actual operating conditions. After components have been validated, it is time to build a system, which occurs on level six. Level seven describes the system prototype demonstration. At this stage, it is important to evaluate the

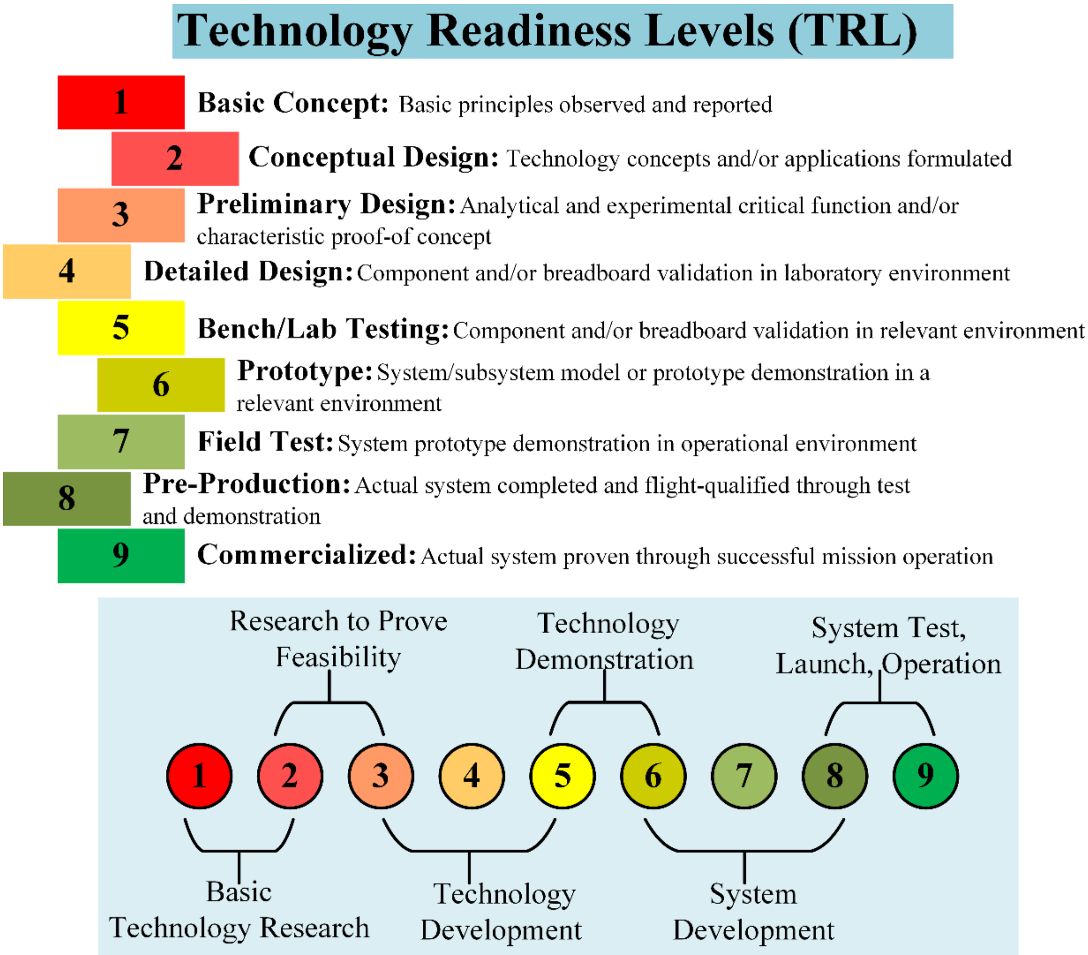

FIGURE 5. Illustration of Technology Readiness Levels (TRLs). Level 1 denotes an immature technology and the increasing levels denote increased levels of maturity, with Level 9 representing the highest level.

system's compatibility with other systems in the environment. At level eight, the technology is evaluated using reliability qualifications testing. At level nine, development has been completed; the design is fixed and the full rate of production has been established. Level nine is characterized by the mature stage of the technology where the technology has been brought to a production level.

The idea behind the Technology Readiness Levels is that the risk associated with a particular technology is inversely proportional to the level completed. For example, the risk of implementing a technology that is on the readiness level of five is roughly 50%, while a technology that has reached the ninth level has a risk factor in the single digits.

B. MANUFACTURING READINESS LEVEL (MRL)

A Manufacturing Readiness Level (MRL) [22], [23] tool was developed by the US Department of Defense (DoD) primarily for their weapons programs. Manufacturing readiness is the ability to use the capabilities of the industrial base to achieve a successful product in the quantity, cost and quality needed. A closely related process is a Manufacturing Readiness Assessment (MRA) [24], which is a formal process to evaluate MRLs to measure the manufacturing maturity and associated risk of key elements of a program. MRAs typically lead to the development of a manufacturing maturation plan (MMP). The process technologies, facilities, workforce, tooling, and supplier base must be identified and ready for effective transition from development to production. It is important to recognize that the assessment of MRL is the critical step towards making a real product. Without this step, the technology is unlikely to ever be practically realized in the timeframe necessary, at the appropriate reliability level and cost. Figure 6 demonstrates the manufacturing readiness levels. A description of the ten levels of manufacturing readiness in a truncated form follows.

1) Manufacturing Feasibility Assessed. This is the lowest level of manufacturing readiness. The focus is on a top-level assessment of feasibility and manufacturing shortfalls. Basic manufacturing principles are defined and observed.
2) Manufacturing Concepts Defined. This level is characterized by developing new manufacturing approaches

Manufacturing Readiness Level (MRL)		
Material Solutions Analysis	1	Basic manufacturing implications identified.
	2	Manufacturing concepts identified
	3	Manufacturing proof-of-concept developed
	4	Capability to produce the technology in a laboratory environment
Technology Development	5	Capability to produce prototype components in a production relevant environment
	6	Capability to produce a prototype system or subsystem in a production relevant environment
Engineering and Manufacturing Development	7	Capability to produce systems, subsystems or components in a production representative environment
	8	Pilot line capability demonstrated. Ready to begin low rate production.
Production and Deployment	9	Low rate production demonstrated. Capability in place to begin full rate production.
Operation and Support	10	Full rate production demonstrated and lean production practices in place.

FIGURE 6. Illustration of the Manufacturing Readiness Levels (MRLs). Level 1 denotes a technology not ready for manufacture and the increasing levels denote increased levels of maturity, with Level 10 representing the highest level.

or capabilities and by applied research. The feasibility of producing a prototype product/component is demonstrated in this phase. It includes identification and study of material and process approaches, including modeling and simulation.

3) Manufacturing Concepts Developed. The first real demonstrations of the manufacturing concepts occur in this phase. Within these levels, identification of current manufacturing concepts or producibility has occurred and is based on laboratory studies. Materials have been characterized for manufacturability and availability, but further evaluation and demonstration is required. Models have been developed in a lab environment that may possess limited functionality.
4) Capability to produce the technology in a laboratory environment. In this phase, processes for manufacturability, producibility and quality have been demonstrated. Manufacturing risks for prototype build and manufacturing cost elements have been identified. Producibility assessments of design concepts have been completed. Key Performance Parameters (KPP) identified. Special needs identified for tooling, facilities, material handling and skills.
5) Capability to produce prototype components in a production relevant environment. Manufacturing strategy is refined at this stage and integrated with Risk Management Plan. Identification of enabling/critical technologies and components is complete. Prototype materials, tooling and test equipment, as well as personnel skills have been demonstrated on components in a production relevant environment, but many manufacturing processes and procedures are still in development. Cost model based upon detailed end-to-end value stream map.
6) Capability to produce a prototype system or subsystem in a production relevant environment. Majority of manufacturing processes have been defined and characterized, but there are still significant engineering/design changes. Preliminary design of critical components completed. Producibility assessments of key technologies complete. Prototype materials, tooling and test equipment, as well as personnel skills have been demonstrated on subsystems/systems in a production relevant environment. Detailed cost analysis includes design trades. Cost targets allocated. Producibility considerations shape system development plans. Long lead and key supply chain elements identified.

7) Capability to produce systems, subsystems or components in a production representative environment. Detailed design is underway. Manufacturing processes and procedures demonstrated in a production representative environment. Detailed producibility trade studies and risk assessments underway. Cost models updated with detailed designs, implemented on a system level, and compared against targets. Unit cost reduction efforts underway. Supply chain and supplier QA assessed. Long lead procurement plans in place. Production tooling and test equipment design & development initiated.
8) Pilot line capability demonstrated. The technology is now ready for a low rate production. Detailed system design is complete and sufficiently stable to enter low rate production. All materials are available to meet planned low rate production schedule. Manufacturing and quality processes and procedures proven in a pilot line environment, under control and ready for low rate production. Known producibility risks pose no significant risk for low rate production. Engineering cost model driven by detailed design and validated. Supply chain established and stable.
9) Low Rate Production demonstrated. Capability is in place to begin full rate production (FRP). Major system design features are stable and proven in test and evaluation. Materials are available to meet planned rate production schedules. Manufacturing processes and procedures are established and controlled to three-sigma or some other appropriate quality level to meet design key characteristic tolerances in a low rate production environment. Production risk monitoring is ongoing. Actual cost model developed for FRP environment, with impact of continuous improvement.
10) Full Rate Production demonstrated and lean production practices in place. This is the highest level of production readiness. Engineering/design changes are few and generally limited to quality and cost improvements. System components or items are in rate production and meet all engineering, performance, quality and reliability requirements. All materials, manufacturing processes and procedures, inspection, and test equipment are in production and controlled to six-sigma or some other appropriate quality level. FRP unit cost meets goal, funding sufficient for production at required rates. Lean practices well established and continuous process improvements ongoing.

As in the case of Technology Readiness Levels, the level of manufacturing readiness is inversely proportional to the risk associated with introducing the technology - the higher the level the lower the risk.

C. BUSINESS AND MARKET READINESS LEVEL (BMRL)

Besides attaining the appropriate technology and manufacturing levels, it is also critical to evaluate the business risk involved in creating a product. Any new technology must primarily demonstrate the market need, either in the existing market or by opening a new market segment. The Business and Market Readiness Level (BMRL) is very closely tied to investment decisions. The BMRLs are simply described by the source of funding, from exploratory programs funded as Research and Development (R&D) to sales in billions of dollars. Figure 7 illustrates the BMRLs on the basis of the source of funding.

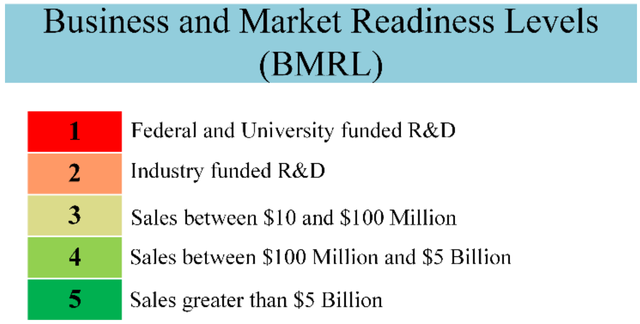

FIGURE 7. Illustration of the Business and Market Readiness Levels (BMRLs) based on the funding. Level 1 denotes a developmental stage and the higher levels up to Level 5 denote a solidly-footed business and market competitiveness.

Moving through levels, from 1 to 5, means that the investment is changing from exploratory and high risk to minor improvements and manufacturing optimization, which carry little risk. As before, the higher the level the lower the risk.

IV. EVALUATION OF THE CURRENT STATUS OF FUEL CELL TECHNOLOGY

As stated previously, the main fuel cell type that is a candidate for transportation, stationary, and portable applications is the proton exchange membrane fuel cell (PEMFC). In this section, an evaluation of the current technological status and challenges for this fuel cell will be presented. For instance, the main identified challenges for the introduction of fuel cells in automotive applications are delineated in Figure 8. Durability and cost are the two most crucial barriers to widespread deployment of fuel cell technology [25], [26].

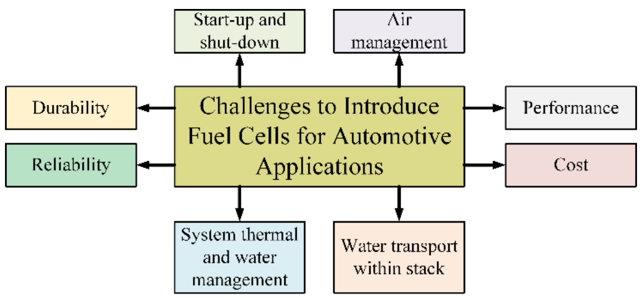

FIGURE 8. The challenges that withhold the deployment of fuel cells for automotive applications in a nutshell.

The majority of fuel cell cost comes from the cost of the catalyst - roughly 80% of the total stack cost. It is important to remember that the platinum catalyst currently used is the same catalyst used by W. Grove 180 years ago and it is still the best catalyst for fuel cells. Because of the high cost of platinum and its limited supply research is ongoing to discover alternatives platinum [27]. Platinum alloys and structured nanoparticles are being investigated for the purpose [28], [29]. Particularly, core-shell nanoparticles with copper-platinum alloy core and platinum shell have been shown to use 80% less platinum in fuel cells [27]. The quest continues for catalyst support materials (such as carbonaceous materials [30]), which can yield a better performance of platinum catalysts at a lower cost. It is, therefore, essential to lower the catalyst cost and at the same time maintain or improve performance. The polymer electrolyte membrane cost is quite low, but membranes add complexity to the system, pose durability risks, and add performance limitations. The technical targets specified by the US Department of Energy (DoE), in collaboration with research institutions and industry, for the catalyst and the membrane are shown in Tables 1 and 2.

TABLE 1. Technical targets for MEA and catalysts [25].

Characteristic	Units	Status in 2017	2025 Target
Heat rejection	kW/°C	1.45	1.45
MEA cost	$/kW	11.8	10
Platinum Group Metal (PGM) total content	g/kW rated	0.125; 105 (150,250 kPa)	≤ 0.10
Durability with cycling	Hours	4100	8000
Performance @ 0.8V	mW/cm^2	306	300
Performance @ rated power guideline	mW/cm^2	890; 1190 (150, 250 kPa)	1800
Robustness (cold operation)		Not tested	0.7
Robustness (hot operation)		Not tested	0.7
Robustness (cold transient)		Not tested	0.7
Loss in catalytic (mass) activity	%	40	≤40% loss of initial
Loss in performance at 0.8 A/cm^2	mV	20	≤30
Electrocatalyst support stability	% mass activity loss	Not tested	≤40
Loss in performance at 1.5 A/cm^2	mV	>500	≤30
Mass activity	A/mg$_{pgm}$ @ 900 mV$_{iR-free}$mV	0.6	0.44
PGM-free catalyst activity	A/cm^2 @ 900 mV$_{iR-free}$A	0.021	0.044

TABLE 2. Technical targets for fuel cell membrane [25].

Characteristic	Units	Status in 2017	2025 Target
Preferred maximum operating temperature	°C	120	120
Area specific proton resistance at			
120°C and water partial pressure 40 kPa	Ohm cm^2	0.054 (40 kPa) 0.019 (80 kPa)	0.02
95°C and water partial pressure 25 kPa	Ohm cm^2	0.027 (25 kPa) (At 80°C, 0.02 at 25 kPa, 0.008 at 45 kPa)	0.02
30°C and water partial pressure 4 kPa	Ohm cm^2	0.018	0.03
−20°C	Ohm cm^2	0.2	0.2
Maximum oxygen crossover	mA/cm^2	0.6	2
Maximum hydrogen crossover	mA/cm^2	1.9	2
Maximum electrical resistance	Ohm cm^2	1635	1000
Cost	$/m^2	15.9	17.5
Durability			
Mechanical	Cycles w/<10 sccm crossover	24,000	20,000
Chemical	Hours with <5 mA/cm^2 crossover or <20% loss in OCV	614	500
Combined chemical/mechanical	Cycles until <5 mA/cm^2 crossover or <20% loss in OCV	Not tested	20,000

From the point of view of planning, these studies reveal a fairly detailed analysis, but it is the overall impression that too many factors need to be improved upon before the technology readiness level can be reached. This puts fuel cell technology in question, at least in the short term. It appears, however, that there is a progression towards achieving the cost and durability targets. It is estimated that the cost of fuel cells reduced by 60% over the span of 12 years, from 2006 to 2018 [31]. Similarly, durability has improved significantly in the same period, albeit no solid numerical data has been found. It is, however, obvious from the available studies that even the fundamental mechanistic and material problems have not been resolved. For example, it is recommended that the following research areas need to be explored to achieve the targets:

- Catalyst: lower Pt loading, Pt alloys, nanoparticles, novel support structures, non-Pt catalysts
- Membrane: Phase segregation control, non-aqueous proton conductors, hydrophilic additives

A. AUTOMOTIVE APPLICATIONS OF FUEL CELLS

As of 2017, a fuel cell power supply for automotive applications of 80kW would cost approximately \$45/kW at 500,000 units/year and \$50/kW at 100,000 units/year [25]. The high-level targets necessary for automotive market entry of fuel cells, according to the US DoE, are provided in Table 3.

TABLE 3. Technical targets for automotive-scale (80 kWe net fuel cell system operating on hydrogen) [25].

Characteristic	Units	Status in 2017	2020 Target	2025 Target
Peak Energy Efficiency	%	60	65	65
Specific Power	W/kg	659	650	900
Cost	$\$/kW_e$	45	40	35
Cold start-up time to 50% of rated power				
@ −20°C ambient temperature	Seconds	20	30	30
@ +20°C ambient temperature	Seconds	<10	5	5
Durability in automotive load cycle	Hours	4130	5000	8000
Unassisted start from	°C	-30	-30	-30

Fuel cell vehicles are a vast area of application of fuel cells. Numerous studies have been conducted in fuel cell vehicles, due to them being non-polluting and green, as opposed to engine driven vehicles [32]. Batteries are also extensively used in vehicles to the point that even second life batteries are also considered for use [33]. Compared to the expansive usage of batteries in vehicles, fuel cells still have a long path to travel, and this can only be done once fuel cells are technologically mature enough to compete with batteries.

B. STATIONARY APPLICATIONS OF FUEL CELLS

The next critical area where fuel cells could play an important role is in stationary applications, such as primary power supply, backup power supply, and combined heat and power (CHP) systems. The main technology development driving forces are energy supply diversification, energy efficiency, environmental benefit, and global economics. Many stationary fuel cell systems have been demonstrated using hydrogen fuel. The key performance requirements for this type of application are the ability to use natural gas or Light Propane Gas as a fuel and be able to achieve very long lifetimes with minimum maintenance. Tables 4 and 5 list the technical targets for stationary fuel cells based on available data from the DoE.

TABLE 4. Technical targets for stationary 1-25 kWe fuel cells operating on natural gas [34].

Characteristics	Units	Status in 2015	2020 Targets
Electrical efficiency at rated power	%	34-40	>45
Equipment cost	\$/kW	2300-2800	1500
Durability	hours	12000-70000	60000

TABLE 5. Technical targets for stationary 100 kW – 3 MW fuel cells operating on natural gas [34].

Characteristics	Units	Status in 2015	2020 Targets
Electrical efficiency at rated power	%	42-47	>50
Equipment cost	\$/kW	1200-4500	100
Durability	hours	40000-80000	80000

The functionality of stationary fuel cells is satisfactory, while durability remains the primary concern. The main technical challenges towards achieving these goals are:

- Fuel processing: cost of desulfurization and heat exchangers, and reformate composition.
- Fuel Cell Stack: MEA to stack communication, MEA degradation and operational ability, and MEA cost
- Power conditioning: inverter cost.
- Balance of Plant (BOP): cost and reliability of pumps, valves, and other components.

In contrast to PEM fuel cells for stationary applications, the high temperature fuel cells (i.e., SOFC and MCFC) have the advantages of being tolerant to impurities in fuel such as carbon monoxide, water management is not an issue, they offer high quality heat, and the system design is much simpler, with fewer parts. Stationary fuel cell systems face significant challenges in improving efficiency and durability while establishing high-volume capacities and further lowering the cost. The functionality of stationary fuel cells is nearly adequate, while the cost still has to be reduced and long-term durability must be confirmed. This application for fuel cells is certainly closer to reality than the automotive market.

C. PORTABLE APPLICATIONS OF FUEL CELLS

Portable fuel cell applications are equally important and as attractive as automotive and stationary applications. The development of successful products for consumer electronics markets will not solve the global energy program, but it can certainly produce a significant reduction in hazardous waste created by disposable batteries; it can offer a potentially lower cost while offering better functionality; and it can also add to the popularity and positive perception of fuel cells. The consumer electronic devices targeted for battery replacement with fuel cells are laptop computers, smart phones, video cameras, two-way radios, portable audio, power tools, video games, and toys. The trends in the portable consumer market reveal the increasing demand for power at the same size. While there are numerous improvements in battery technology, it has become obvious that a large gap has been created between the power demand and present battery technology capability. It is highly unlikely that novel battery systems can be discovered and it is universally agreed that the future is in fuel cells. The specifics of portable applications impose very tough demands on the fuel cell power supply. The choice of fuel is one of the critical issues because of the need not only for fuel storage solutions, but for recharging these devices.

Liquid fuels seem like an obvious solution and methanol, for example, has been used in fuel cells for its high energy density [28]. There are two possible methods to use methanol as a fuel. One is a direct methanol fuel cell (DMFC) in which methanol is directly oxidized on the anode of the fuel cell. As described earlier in the text, this method suffers from two major technical problems. First, the anodic oxidation reaction of methanol requires a special electrocatalyst, and second, methanol tends to migrate through the proton conducting membrane and react on the cathode, severely reducing the fuel cell power and fuel efficiency. An alternative approach to avoid these serious problems is to store methanol as a fuel, but include an intermediate process step in which methanol will be converted in a so-called ''reforming reaction'' to hydrogen, which then reacts on the anode of the fuel cell. This method offers much higher power densities and avoids the problems of direct methanol reactions. However, a new component is added to the system, so the more efficient fuel cell reaction comes at the cost of increasing the complexity and overall size of the system. Because of the need for very precise control and intricate functionality, the whole portable fuel cell system becomes very complex and typically comprises four major sub-systems: fuel cell stack, fuel storage, balance of plant (valves, pumps, sensors, etc.), and electronics (pump drivers, ''buck'' converters, boosters, etc.).

Direct methanol fuel cells are rather inefficient with only 20% of the fuel being converted to electricity, while the remaining 80% is more often than not dissipated as heat or other losses. Of the 20% converted to electricity, only approximately 65% becomes net power, while the remaining 35% is used to drive the balance of plant components. Consequently, the total portable fuel cell system efficiency is roughly 13%.

The performance target for portable fuel cell devices calls for energy densities of 650 Wh/L for 5-50 W devices and 900 Wh/L for 100-200 W devices [35]. The cost is not a concern for this application of fuel cell technology and durability is a marginal issue because of the relatively low requirement of 5,000 hours. The size of the system is the only critical issue along with minor considerations, such as ease of refilling. This fuel cell application is most likely the closest to reality.

In summary, fuel cell technology, in particular PEMFC, requires some critical improvements to become competitive in the energy field. On a component basis, major improvements are needed for the electrodes and the membrane. For transportation applications, a cost that is many times lower is required and major improvements in the fundamental catalytic rate, catalyst utilization, and stability under load are necessary. For stationary applications, improved catalyst efficiency and lower loadings are needed. For portable applications, an improved methanol oxidation catalyst is the key. For transportation applications, the PEMFC membrane must be improved for better durability, better low relative humidity performance, and lower cost. In portable fuel cell applications, a novel membrane must be developed to better handle the methanol crossover. And most critically, for all three applications, high-volume manufacturing methods must be developed. Overall, in all three applications, there are many problems and issues with lots of room for improvement, but there are also reasons for optimism.

V. DEVELOPMENT OF FUEL CELL TECHNOLOGY READINESS LEVELS (FCTRL)

The combination of three readiness level tools has been used to create a new and first of its kind fuel cell readiness level assessment tool. The readiness level evaluation method is comprised of 7 levels of maturity with 3 sub-levels (i.e., questions) in each level. The levels or questions were applied from the established description of readiness levels in the three tools and adapted to fuel cell technology. This approach conveys the intention that fuel cell readiness depends critically on the degree of development not in one, but in all three critical aspects: technology, manufacturing and business/marketing. In the case of technology such as fuel cells, just one of the tools may give a misleading result. This is usually expressed as a false overstatement of technology readiness without manufacturing support and a disregard of business and market conditions. As will become evident from the description, not all levels from the original tools were used because fuel cells are in a specific development stage and some of the technology differs enough from the originally intended technologies. These are the fuel cell readiness levels (Figure 9).

Level 1: *Proof-of-concept*

- Laboratory proof of concept for novel fuel cell types (for example, untested fuel for direct oxidation, new oxidant, a new membrane, or a completely new electrode and stack design).
- Power density > 10 mW/cm^2 demonstrated.
- Membrane conductivity < 0.10 S/cm.
- Major design novelty demonstrated (for example, novel catalyst shown to be functional or liquid electrolyte separation using laminar flows verified).

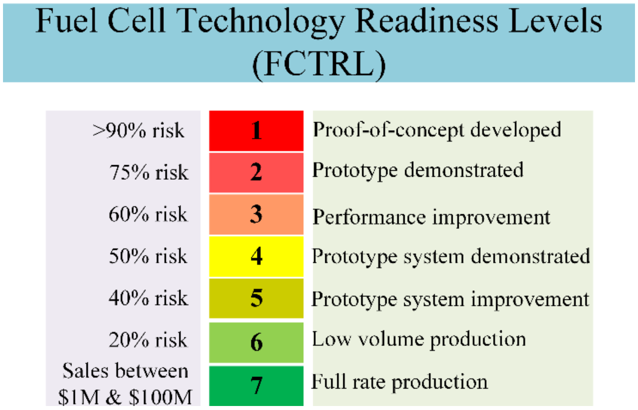

FIGURE 9. **The seven levels of the FCTRL tool. Level 1 indicates a rudimentary stage of the fuel cell technology and as the levels go higher, the technology is said to be developed gradually.**

- University or government funded; rarely privately funded because the concept might not be technologically feasible.
- The risk for technology success (for an investor) is > 90%.

Level 2: *Prototype demonstrations*

- Prototype demonstration with > 50 mW/cm^2.
- No fundamental operational problems such as incompatibility of the electrolyte, electrodes, or reactants, no major design challenges identified.
- Successful operation at the above power density in short stacks (3-5 cells).
- Uninterrupted operation for 1 hour
- Manufacturing system cost estimate: < \$500/kW for automotive and stationary fuel cells, < \$10/W for portable fuel cells.
- Performance modeling and simulation confirms design validity.
- This stage could be industry or government funded, but it is a typical entry point for discussions towards \$2-5 million in private (venture capital) funding.
- The risk for investment at the end of this phase is 75%.

Level 3: *Performance improvement*

- Non-integrated prototype demonstration at > 200 mW/cm^2 power density for automotive and stationary, and 100 mW/cm^2 for portable applications.
- Demonstrated capability to produce technology in a laboratory environment.
- Breadboard system efficiency > 40% when using hydrogen as fuel, 25% when using other fuels.
- Thermal management and water transport solutions either demonstrated experimentally or presented clearly in the design.
- Materials and components characterized for manufacturability and availability.
- Manufacturing risks identified for full prototype build and producibility assessments completed.
- Special needs identified for tooling, facilities, material handling, and skills.
- Detailed cost analysis for the final product completed and corresponds to general industry expectations: < \$50/kW for automotive, < \$1000/kW for stationary, and < \$15/kW for portable applications.
- Typically, private or industrial funding at the level of \$2-5 million.
- The risk of investment at the end of this phase is 60%.

Level 4: *Prototype system demonstration*

- Complete, integrated fuel cell system including short stack, balance of plant, fuel storage and supply, and electronics demonstrated in a prototype-simulating, real production environment.
- For low temperature fuel cells simulated, realistic fuels should be used.
- If the technology involves using hydrogen as fuel, a clear supporting technology and the overall scenario for hydrogen production should be identified. Complete system manufacturing and efficiency analysis should be completed and compared with existing technologies. Social, political, and economical consideration can be taken into account.
- System efficiency > 50% for automotive and stationary systems, and 30% for portable systems.
- Catalyst loading < 1 mg/kW demonstrated.
- All critical balance of plant components identified and incorporated.
- Air, thermal, and water management schemes shown to function properly.
- No major design changes should occur on this or subsequent levels, otherwise the technology should be considered new.
- Prototype demonstration for durability beginning in this phase with a goal of 50,000 hours for stationary, 5,000 hours for automotive, and 3,000 hours for portable applications. (Durability testing should be completed for automotive and portable systems before the next phase).
- Identification of critical enabling technologies completed.
- All manufacturing processes, in particular catalyst deposition and membrane fabrication or attachment to electrodes, defined and characterized, and their producibility verified.
- Long-lead supply chain elements identified.
- This phase would require \$10-15 million.
- The investment risk at the end of this phase is 50%.

Level 5: *Prototype system improvement*

- Prototype performance improved to > 1kW/cm^2 for PEM systems for automotive and stationary applications and 200 W/cm^2 for portable applications. (Different PEM systems such as those based on Polybenzimidazole (PBI) membrane have different power density and performance standards).

- Platinum metal content in prototype stacks < 1.5 g/kW and < 1 mg/cm^2.
- Catalyst cost < \$50/kW in low-volume production. Clear cost model that leads to <\$8/kW in high-volume production.
- Catalyst degradation and electrochemical area loss mechanisms clearly understood and controlled.
- Mass activity > 0.1 mA/cm^2, specific activity > 150 mA/cm^2.
- Membrane cost < \$80/m^2 in low-volume production. Clear cost model that leads to <\$40/m^2 in high-volume production.
- Technology preparation for low-rate production.
- Supply chains are established and ready.
- Durability testing completed without failures or performance decrease for automotive and portable systems, on-going for stationary systems, but complemented with reliability analysis and predictive methods.
- Supplier chain and supplier quality assurance (QA) evaluated.
- High-volume production tooling and test equipment design and development initiated.
- The development on this level can cost from \$5 to \$10 million. Orders obtained for first low-rate production systems.
- The investment risk after successfully completing this level is 40%.

Level 6: *Low volume production*

- Design stable and verified through complete reliability testing and modeling.
- Any design changes are limited to quality and cost improvement.
- Actual fuel cell system completed and verified through long-term testing.
- Low-volume (1000 systems per year) capability demonstrated. Capability in place to begin full rate production (FRP).
- Materials available to meet planned rate production schedules.
- Manufacturing processes and procedures are established and controlled to three-sigma or some other appropriate quality level to meet key design characteristic tolerances in low rate production environment.
- Production risk monitoring on-going.
- Sales from low-rate production > 100 systems offset production and operational costs.
- The investment risk with successful completion of this level is roughly 20%.

Level 7: *Full rate production*

- Fuel cell system production on the order of > 1000 systems a year.
- Adjustments can only be made to operating conditions, for example reactant flow rates, relative humidity levels, or voltage-current operating point.
- All processes are controlled to 3σ or appropriate quality level.
- Full production cost goal meets the target.
- Continuous improvement processes are in place.
- This is the highest level of technology readiness
- The sales at this level are between \$1 million and \$100 million.

Using the developed FCTRL methodology, any fuel cell technology or product can be evaluated. The actual procedure is simple, whereby the aspects and performance characteristics of a product under evaluation are measured against each criterion starting from Level 1. If ALL criteria on one level of readiness are found to be accomplished, then the evaluation moves on to the next level. The level at which any of the criteria (using reasonable judgment by a trained evaluator) is found not to be achieved is then assigned as the readiness level of the technology or the product. The tool developed and presented here is shown in a form suitable for PEM fuel cells. Evaluating other fuel cell types requires appropriate modifications of the evaluation tool. A specific evaluation tool will be developed for each fuel cell type and application. Furthermore, the specific performance targets must be constantly revisited and corrected if necessary.

VI. GENERAL ASSESSMENT OF THE FC TECHNOLOGY BASED ON THE DEVELOPED FCTRL TOOL

The Fuel Cell Technology Readiness Level (FCTRL) tool is most suitable for evaluating fuel cell technology of a specific type and for a specific application. The primary intention of the authors was to give potential investors, analysts, users, and others interested in technology valuable criteria for evaluating the technology. The FCTRL tool can also be used for generalized assessment of fuel cell technology whereby the majority of non-specific criteria will be used and the best performing fuel cell type may be taken into account. This approach, of course, carries many assumptions and cannot be considered completely accurate, but has some validity for assessing the maturity of fuel cell technology in general. The evaluation also looks primarily at PEM fuel cells arguably the most advanced and popular fuel cell type. PEM fuel cells have been frequently proclaimed market ready, but those claims have never been supported using objective methodology.

In short, fuel cells have been known for about 180 years, so all major fuel cell types and combinations of electrolyte and electrodes pass all the criteria in Level 1.

Most well-known fuel cells that are available on the market in limited quantities pass Level 2 criteria. However, some fuel cell developers, now and throughout history, have chosen to ignore and by-pass important manufacturing readiness considerations in a rush to demonstrate technology performance. Consequently, there are many fuel cell products offered that did not have manufacturing cost estimates or modeling and simulation performed. In addition, it should be understood that the evaluation tool looks primarily at a new development and contains many criteria/guidelines for early implementation of good manufacturing and reliability practices. Many ''established'' fuel cell products fail those criteria, which is partly the reason they never fully succeeded in the marketplace despite limited production.

The majority of recognized fuel cell types and products pass the criteria for Level 3, with the exception of following systematic manufacturing preparation stages and analysis. Most portable fuel cell producers were found to hopelessly continue the development stage and go towards production without satisfying the absolutely necessary power density criteria. The expectation of course is that the technology would ''catch-up'' and the performance would improve, while the manufacturing path is being pursued in parallel, usually in an unsystematic manner.

Level 4 is largely challenging for most fuel cell technologies known. Only a few products pass the criteria of overall efficiency, catalyst loading, water management, durability, and cost estimates for high-volume production. The real question is why those developers continue to make fuel cell products when it is unreasonable to expect any real market penetration. The answer is probably in the expectations of relaxed market conditions, specifically regarding the cost and reliability. As with most other energy technologies, it is often not the question if the technology can deliver, but it is about the cost at which it can deliver. Nothing is truer for fuel cells. The reasons that fuel cells have shown very little progress in nearly two centuries and still remain viewed as attractive energy conversion devices is the ability to demonstrate fuel cell functionality. However, these demonstrations have always been done with little or no consideration of the cost per kW. Once these issues are brought into the discussion, fuel cells almost inevitable lose all previously perceived advantages. The FCTRL tool makes an attempt to give realistic assessment criteria for a fuel cell technology level and eliminate such misleading cases. This insertion of the technology readiness reality has been done in the FCTRL tool by incorporating a model of systematic manufacturing implementation principles very early in the development process.

Most of the select few fuel cells that pass Level 4 find themselves locked solidly on Level 5. The criteria for Level 5 are very challenging, but realistic, especially in regards to manufacturing cost prediction. At this point, no manufacturer has announced clear roadmaps towards major reductions in cost. Apart from that, there are very few fuel cell manufacturers whose products fully satisfy Level 5 criteria.

Level 6, suggesting low-volume production, has been realistically reached only by two developers, again with the exception (or criteria relaxation) that no clear reduction in manufacturing costs is offered. These two companies have a low-rate volume production. They have, however, not revealed their product control criteria and it is very likely that they do not have 3σ quality in place. Based on the fact that there are currently no known methods for the high-volume production of fuel cells, it is also very doubtful that they have manufacturing processes, procedures, and capabilities in place for a full-rate production.

In the authors' opinion, there are currently no fuel cell products that can be assigned Level 7 technology readiness. As discussed above, even notable efforts that can tentatively be characterized as being on Level 6 readiness likely don't satisfy all the elements necessary for the progression to the final readiness level. The most realistic assessment places a majority of the established fuel cell technologies on Level 5 readiness and probably only two products tentatively on Level 6. This assessment should be qualified to exclude fuel cells for space applications.

VII. CONCLUSION

A new evaluation tool based on technology readiness levels, manufacturing readiness levels, and business and market readiness levels has been developed for the assessment of fuel cell technology. The tool has been developed by modifying the existing technology and manufacturing readiness levels from the aerospace and defense industries and making them appropriate for fuel cell technology evaluation.

Based on the technology validation presented, it is evident that fuel cells are in a strange position for technology commercialization. On one hand, the long-term promise is a strong driving force, but at the same time, it is very clear that in some areas, fuel cells are still in their technological infancy. While manufacturers and governments are planning reductions in cost, they are not doing that on the manufacturing level, but on the fundamental level. This indicates a low manufacturing readiness. If the technology is not ready on a fundamental level, with designs and materials clearly defined, then it becomes obvious that manufacturing and commercialization are premature. Furthermore, fuel cell technology has barely embarked on resolving the system integration issues, such as combined heat and power, and numerous performance challenges, such as reactant impurities. This new evaluation tool has the potential to provide the most exact evaluation of fuel cell technology reported so far. Further improvements to the FCTRL tool will be reported in subsequent works. Specific examples of the evaluation of certain fuel cell types in defined applications will also be presented shortly. This tool could become a method that will help fuel cell technology find its right place in the inevitably changing energy conversion landscape. A similar approach can be taken to evaluate the technological readiness of other energy storage technologies or other battery technologies, for instance Li-ion batteries.

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