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Technological barriers and research trends in fuel cell technologies: A citation network analysis

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ABSTRACT

Fuel cell technologies have long been recognized as one of the most promising future energy solutions. Nevertheless, major technological barriers hinder the potential realization of this clean energy source. Citation network analysis methodology is used here to identify major research trends, critical technological issues, and proposed resolutions to raise the effectiveness of investment of R&D resources in fuel cell technology development.

The main path analyses identify two research streams for the Proton-Exchange Membrane Fuel Cell (PEMFC) and Direct Methanol Fuel Cell (DMFC) technologies. Analyses of cited publications show that most of the technological barriers for PEMFC have been addressed and that performance has reached an acceptable level. On the other hand, DMFC still suffers from methanol and water crossover problems. Multiple main path analysis identifies specific research groups working on technological problems in DMFC. The Direct Formic Acid Fuel Cell (DFAFC) and Direct Ethanol Fuel Cell (DEFC) have recently emerged to address the toxicity of methanol, while DMFC performance is being enhanced through research on porous carbon plates, water transportation, and methanol concentrations, and the research group at Micro DMFC is applying fuel cells in electronics devices. Despite considerable research on Solid Oxide Fuel Cell (SOFC), its research stream does not appear in the main paths, most likely because of a broad divergence in research subjects. Growth curve analysis forecasts that fuel cell research is in the growth stage and will enter maturity in 2018. Although emerging technologies show advantages in performance and cost, the findings presented here can raise the effectiveness of critical research project selection, thus increasing the likelihood of success.

1. Introduction

Growing global energy demand has increased the cost of fossil fuels and the volume of environmentally harmful greenhouse gases. To reduce pollution and minimize dependency on fossil fuels for energy generation, alternative and clean sources of energy need to be exploited. In 2010, global total new investment in clean energy had tripled from only five years before [1], indicating an aggressive search for new, clean and renewable energy sources. Among these renewable energy technologies, fuel cells can be used in a wide range of applications, including portable electronics, stationary electricity generators and passenger vehicles [2]. Sales of fuel cells exceeded $750 million in 2010 [3].

Despite what is anticipated to be a bright future, fulfilling the full commercial potential of fuel cells still requires overcoming some major technological barriers. Identification of these specific technological barriers and matching research trends will facilitate effective industrial planning and investment. Investment in fuel cell R&D has fed a growing body of literature and publications [4].

Several previous surveys have reviewed DMFC articles from various perspectives. Liu et al. [5] reviewed over 100 articles on anode catalysis in direct methanol fuel cells and suggested new R&D directions for DMFC anode catalysis. Neburchilov et al. [6]

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outlined the prospects for DMFC membranes and evaluated the membranes in terms of various properties. They suggested that hydrocarbon and composite fluorinated membranes have the greatest potential to provide low methanol permeability and high durability at low costs. Ahmad et al. [7] reviewed the hybrid membranes for DMFC applications, and found that Nafion-based membranes had dominated the membrane market over the past four decades.

Other researchers contributed survey articles related to PEMFC. Mehta and Cooper [8] reviewed PEMFC design and manufacturing, examining membrane electrode assembly manufacturing options, synthesis processes, and bipolar plate fabrication options. Cheddie and Munroe [9] surveyed the literature on PEMFC modeling. Cheng et al. [10] examined over 150 articles on contamination issues in PEM hydrogen fuel cells, and concluded that contamination affects fuel cell performance in terms of electrode kinetics, conductivity, and mass transfer. Tawfik et al. [11] comprehensively reviewed studies on metal bipolar plates for PEMFC. Li and Sabir [111] reviewed the flow-field designs of bipolar plates in PEMFC and listed pros and cons of various flow-field layouts. Schmittinger and Vahidi [112] surveyed the main parameters influencing the long-term performance and durability of PEMFC. They found that the main causes of short life and performance degradation are poor water management, fuel and oxidant starvation, corrosion and chemical reactions in the cell components. Bezerra et al. [12] reviewed over 120 articles regarding the effect of heat treatment on the catalytic activity and stability of PEMFC catalysts. They compared the pros and cons of each catalyst and concluded that more innovative heat-treatment processes are needed to enhance fuel cell catalyst activity and stability. Zhang et al. [13,14] reviewed the literature on accelerated stress tests of MEA durability and catalyst degradation mechanisms of PEM fuel cells.

Some researchers have surveyed articles on different types of fuel cells, such as microbial fuel cells (MFCs) [15], microfluidic fuel cells [16], direct borohydride fuel cells [17], alkaline fuel cells (AFCs) [18], biofuel cells [19], and solid oxide fuel cells (SOFCs) [20–22]. Rismani-Yazdi et al. [15] reviewed the cathodic limitations in MFCs. Kjeang et al. [16] surveyed the development of MFC technology from 2002 to 2009, with an emphasis on theory, fabrication, unit cell development, performance, design considerations, and scale-up options. Liu and Li [17] examined the development of direct borohydride fuel cell technology and concluded that the BH4-electro-oxidation is determined by the catalyst used and BH4 concentration at the catalytic sites. Bidault et al. [18] reviewed the advantages and drawbacks of the gas diffusion cathodes of AFCs and concluded that noble metal and non-noble metal catalysts show good performance. Willner et al. [19] surveyed assembly methods for integrated enzyme-based biofuel cells. In SOFCs, Shaigan et al. [21] reviewed progress in the development of coatings, surface modifications and alloys for ferritic stainless steel interconnects. Zhang et al. [22] studied integration strategies for SOFCs. Lawlor et al. [20] reviewed stack design issues and research activities of micro-tubular solid oxide fuel cells (MT-SOFCs).

Other researchers have contributed to the study of fuel cell from various other fields. Pettersson et al. [23] surveyed developments in electrodes. Brett and Brandon [24] reviewed the materials and characterization methods for polymer electrolyte fuel cell flow-field plates. Qi et al. [25] examined the integrated fuel processor for hydrogen generation. Yilanci et al. [26] studied solar hydrogen production methods.

Although many previous articles have reviewed the literature on fuel cells, these surveys only focused on specific aspects of fuel cell techniques or applications. With a newly developed bibliometrics and citation network analysis, the present study covers 7313 articles on eight types of fuel cells from 1965 to 2011. To our knowledge, this is the most exhaustive review of the fuel cell literature. Previous individual reviews only covered one hundred articles at most [5,10,12] and concluded results based on subjective judgments. The present study adopts an objective and systematic approach, because the knowledge diffusion paths generated are based on the citation data provided by the authors of each article.

As technological developments are usually based on prior findings [27], the bibliometrics of technology publications present a rich source of information on the dissemination of knowledge [28]. Daim et al. [29] applied bibliometrics to forecast emerging technologies along with patent analysis. Woon et al. [30] used bibliometrics and distributed generation to highlight key trends in related technological developments. Among bibliometric methods, citation network analysis is a powerful tool for reviewing scientific activities [31] and tracing knowledge flows within a particular subject [28,113]. Citation analysis is applicable to patent databases for assessing future technological impacts [32], and for developing technological roadmaps [33] or new product designs [34]. However, applications of bibliometrics and citation network analysis for research journal papers to identify research frontiers are relatively rare.

Through citation network analysis, Kajikawa et al. [4] confirmed the rapid growth of demand for fuel cell and solar cell technology research. Verspagen [27] explained the development trajectory of fuel cell technologies through patent citation networks. Few fuel cell trajectory studies have aimed to identify the major technological barriers to mass application. Therefore, this research uses main path analysis in academic paper citation networks to identify the latest development trends for fuel cell technologies along with their associated technological barriers and breakthrough solutions. It also forecasts life cycle stages for fuel cell technologies through the growth curve analysis of an accumulated number of relevant academic articles. The research results are expected to increase the effectiveness of investments in fuel cell technologies.

2. Data and methods

2.1. Data

Data for research articles related to fuel cell technologies were extracted from the Web of Science (WOS). The WOS has a web-based user interface allowing access to citation information compiled by the Institute for Scientific Information (ISI). The WOS offers six databases, including the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI), Conference Proceedings Citation Index (CPCI), Index Chemicus and the Current Chemical Reactions. The WOS contains more than 49 million records from over 12,000 high impact journals, featuring more than 760 million individual cited references. Our database query spanned from 1965 to August 2011.