CleanEnergy States Alliance

Clean Energy & Fuel Cells

IMPLICATIONS FOR INNOVATION STRATEGIES FROM HISTORIC TECHNOLOGY TRANSITIONS

A Report from the Public Fuel Cell Alliance

The Public Fuel Cell Alliance is a project of the
Clean Energy States Alliance, a 501(c)(3) nonprofit organization
managed by the Clean Energy Group.

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Public Fuel Cell Alliance

The Public Fuel Cell Alliance (PFCA) is a coalition of state and federal agencies working together to accelerate the development and deployment of fuel cell and hydrogen infrastructure development. The PFCA was organized as a special project of the Clean Energy States Alliance (CESA) a 12-state consortium dedicated to supporting renewable power technology development. CESA is managed by the Clean Energy Group (CEG), a noprofit organization. Further information on both organizations is provided at the CESA web site *www.cleanenergystates.org* and specific information on the PFCA can be obtained at *www.cleanenergystates.org/jointprojects/fuelcells.html*.

The PFCA is dedicated to linking federal and state public funding programs through regionally-based initiatives to better serve these state objectives and to provide a focus for industry building activities. A primary objective of the PFCA is to be a conduit for information exchange among its members who are primarily public government entities. The PFCA members recognize that a broader flow of information is necessary for their development of relevant and efficient public programs that are designed to benefit the fuel cell and hydrogen industries.

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Preface

This is the first in what is expected to be a series of papers on technology innovation and clean energy. In this paper, Professor Hargadon has outlined several provocative approaches to fuel cell market development. He applies new academic thinking to our work with public fuel cell and hydrogen infrastructure programs.

In the last few years, states have become the new leaders in commercializing these technologies. Around the country, states are taking bold steps to move to a hydrogen-based economy. There is a great deal of experimentation underway, with many states developing plans for their hydrogen highway, supporting fuel cell activities or developing strategies and mechanisms to support these industries.

Many have agreed to come together through the Public Fuel Cell Alliance (PFCA), a project of the Clean Energy States Alliance (CESA), a nonprofit organization managed by Clean Energy Group.

The PFCA is a coalition of state and federal agencies working together to accelerate the deployment of fuel cell and hydrogen infrastructure technologies across the country. It is the only nonprofit organization in the US that coordinates public funders of fuel cells and hydrogen technologies at the state and regional level. We have begun developing a series of regional initiatives to make these public programs more effective, to achieve their environmental purposes, and to produce tangible benefits from technology innovation.

There are many challenges to bringing these technologies into mainstream markets. One critical need is to develop better business models for technology innovation that can inform and support public policy programs.

Professor Hargadon has begun this exploration, bringing to bear strong academic rigor to these challenges. We expect this paper to set the stage for more in-depth collaboration about clean energy with him and other researchers and strategic thinkers.

Lewis Milford
Cameron Brooks
CLEAN ENERGY GROUP
Editors

Executive Summary

This paper provides a framework for evaluating the path from research to the commercial applications for hydrogen fuel cells. The adoption and widespread use of new energy technologies—whether in production, distribution, or consumption—follows the typical S-curve of adoption. Successfully developing clean energy will require attention not just to advances in basic and applied sciences, but also to the commercial dynamics that surround emerging technologies and represent the "tipping point" signaling rapid and widespread adoption. Programs that ignore these vital steps in the path from research to commercialization undermine the likelihood of achieving their stated goals.

To convert research into meaningful technical and social changes, it is necessary to focus on the characteristics of the commercial ventures that first introduce a new technology: (1) the extent to which a new venture builds on elements of existing systems rather than constructs wholly novel enterprises and (2) the extent to which a new venture exploits existing market structures and consumer dynamics rather than attempts to overturn them. Business models that minimize these risks to commercial success can be used to both guide research and evaluate research projects.

There are several implications of this framework for managing clean energy research:

1. The investment portfolio should be balanced across the spectrum of near- and long-term research. Long-term research advances basic and applied sciences; near-term research focuses on adapting existing technologies for use in new markets and new applications.

2. Commercialization efforts in niche applications, building on existing technologies, often create infrastructure and learning-by-doing that shape (and facilitate) the subsequent path of successive technological changes.

3. Long-term research should include the development and use of business modeling to make explicit the research choices that affect the commercial potential of an emerging technology, and to ease the transition from long-term research to near-term to, ultimately, market deployment.

4. Third-party organizations can assist in this path to commercialization by bridging disparate research environments (e.g., between federal, state, and local) and by providing business development capabilities not traditionally found in research laboratories.

1.0 INTRODUCTION

This paper provides a framework for evaluating the transition from research to commercial applications of hydrogen fuel cells. This is an especially difficult challenge for clean energy technologies, whose promise hinges on the widespread adoption and use of new and alternative technological systems. For example, large scale research expenditures in nuclear power, synfuels, electric vehicles, methanol, compressed natural gas, and corn ethanol have had relatively little effect, to date, on the prevailing patterns of energy production, distribution, and consumption.

While the theoretical advantages of emerging technologies offer justification for their pursuit, these advantages only partially predict their likelihood of widespread diffusion. The network effects triggered by actual adoption and use (e.g., the competing video recording technologies of Betamax and VHS) can easily overcome the inherent technical or economic superiority of any one technology. In this way, the particular characteristics of the commercial ventures that introduce a new technology are as important in determining the success (and timing) of technology transitions.

Based on the historical analysis of previous technological transitions, this paper briefly describes the underlying dynamics that make technological change difficult, and the research and development strategies that have successfully exploited these dynamics to enable widespread diffusion. This paper identifies two central characteristics:

1. the extent to which a new venture builds on elements of existing technological systems rather than construct wholly novel enterprises, and

2. the extent to which a new venture exploits existing market structures and consumer dynamics rather than overturn them. Business models that minimize these risks to commercial success can be used to both guide research and evaluate research projects.

Research into promising new clean energy technologies such as fuel cells should be augmented with greater understanding of how technology transitions unfold, as such a better understanding has critical implications for how research is conducted, what objectives are set, and how progress is measured.

1.1 LONG TAILED INNOVATIONS

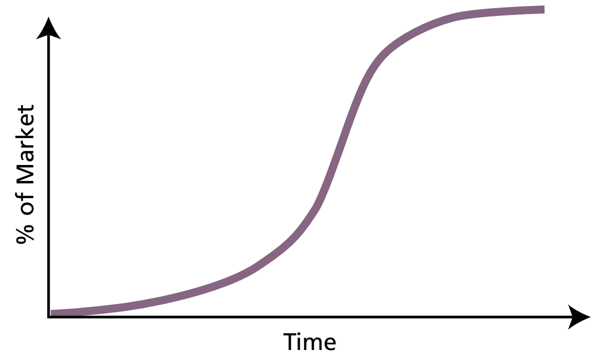
> ***Build a better mousetrap and the world will beat a path to your door.***

Ralph Waldo Emerson famous advice has fueled more than a few technological ventures. But the advice is wrong. Since the US patent office opened in 1838, there are 4,400 patents issued for mousetraps. 40 new patents are issued each year, though only two dozen have made any money and only two dominant designs exist: the spring trap and the sticky pot. The spring trap, still the most dominant, was developed in the 1890s, the sticky pot, in the 1970s.[1]

Similar stories could be told of the millions spent in developing early electric vehicles, synthetic fuels,

Segway—a Mousetrap on Wheels

A recent—though still relatively contained—technology venture, the Segway Human Transporter, illustrates the danger of trusting Emerson's advice. Introduced in 2002, the Segway is a self-balancing, electric-powered, two-wheeled vehicle intended for personal transportation. The Segway represented $100 million in research and development investments, and produced such technical achievements as a gearbox tuned to hum—in harmony—at the frequencies of musical octaves. Billed as a technological revolution in transportation, it was designed to be a better mousetrap. It's founder and investors believed over 600,000 units would sell in the first year and yet, based on recently released numbers, it sold roughly 6,000.



compressed natural gas vehicles, and other alternative energy and transportation technologies of the past half-century. The pursuit of the better mousetrap often leads engineers and scientists towards R&D activities that maximize the performance of a new technology—that build the best possible mousetrap—while denying the business concerns that would ensure commercial adoption and use.

Early efforts to develop and introduce technologies—even the most revolutionary—can take decades, if not centuries. The S-curve of adoption (see figure 1), which tracks the market adoption of a new technology over time, tends to have an exceedingly long initial tail (or ramp) before crossing the inflection point and entering a period of rapid diffusion and growth. Too long a tail, it turns out, to support most early pioneers (see sidebar on past technology transitions).

Past Technology Transitions

- The steam engine, the single technology most responsible for sparking the first industrial revolution, had been around for almost a century before James Watt (in 1785) improved on Thomas Newcomen's (1712) improvements on Thomas Savery's (1698) machine to pump water out of mines. It took another 16 years, when one of Watt's engineers developed the planetary gear system, for the steam engine to become the general-purpose engine that revolutionized industry.
- The first electric lights burned roughly 80 years before Edison introduced his system of electric lighting. Indeed, Edison's original patent application for the electric light was rejected, it was reported in the January 18th, 1879 issue of Scientific American, because "Edison's invention was an infringement upon that of John W. Starr, of Cincinnati, who filed a caveat for a divisible light in 1845."[8] However, it was not until the development of a commercially viable electric generator in the 1870s that electric lighting began to spread dramatically and the first electric lights, in use for over a decade before Edison introduced his system, were arc-lights used to light city streets, parks, and large theaters (by 1884, there were over 90,000 arc lights in use throughout the United States).
- Finally, the transistor first emerged in 1947 as a replacement for mechanical switches and tube amplifiers in the telephone system. It didn't become a general-purpose device until after the subsequent development, over the next three decades, of integrated circuits, magnetic storage disk drives, and the architecture and software (assembly language, operating systems, and applications) of computing systems.

What histories of the steam engine, electric light, and transistor (and many others) reveal is that technological revolutions take time. The rapid adoption of a technology follows a long and slow accretion of changes. This much we know. What we don't know is what causes the upward turn, the tipping point when the technology moves from being relatively unknown to becoming widely accepted? This is a critical question because for every technology that turns upwards on its adoption curve, many more drift into obscurity. If we are investing in a particular technology—like hydrogen fuel cells—we must understand what can be done to ensure it gains widespread adoption, and relatively soon.

2.0 THE ORIGINS AND IMPACTS OF REVOLUTIONARY TECHNOLOGIES

The theoretical advantages of emerging technologies, what makes for a "better" mousetrap, only partially predict the ultimate adoption and use of an emerging technology. Equally important are the particular characteristics of the commercial ventures that introduce a new technology: (1) the extent to which a new venture builds on elements of existing technological systems rather than attempts to construct wholly novel enterprises and (2) the extent to which a new venture exploits existing market structures and consumer dynamics rather than overturn them. We discuss each of these in turn.

2.1 THE RECOMBINANT ORIGINS OF INNOVATIVE VENTURES

Popular discussions of innovation often confuse the origins and impacts of a new technology—revolutionary versus evolutionary, radical versus incremental. But do the revolutionary changes that follow an innovation really require revolutionary origins? Closer studies of the technical details of major innovations suggest the opposite: that it is the recombinant (rather than inventive) nature of revolutionary innovations that contribute to their dramatic effects.[2]

For example, Henry Ford didn't invent mass production so much as combine elements of technologies that were already developed and in use, some for almost a century, in other industries. He found the technologies of interchangeable parts already in use in armory production and watchmaking. He found the technologies of continuous flow production already in use in canneries, granaries, and breweries. And he found the assembly line in use in the meatpacking plants of Chicago. Ford once even testified:

> ***I invented nothing new. I simply assembled into a car the discoveries of other men behind whom were centuries of work… Had I worked fifty or ten or even five years before, I would have failed. So it is with every new thing.***[3]

Ford understood that the revolutionary increases in productivity that came from his mass production techniques depended on the centuries of work that laid the groundwork and provided the people, the ideas, and the machines that he brought together to build his Model T. If Henry Ford had to develop the manufacturing process from scratch, train his engineers in their use, and imagine the myriad details associated with such a complex enterprise, he likely would have failed.

William Gibson once remarked, “The future is already here, it’s just unevenly distributed.” The ability of new technologies to suddenly and rapidly diffuse through a market stems—in part—from entrepreneurs finding ways to exploit the “discoveries of other man behind whom [are] centuries of work” rather than attempt to invent the future. These entrepreneurs innovate by bridging otherwise disconnected domains, recognizing how the resources of one domain can be used to satisfy the needs of another, and building enterprises that bring these pieces together. In this way, they have been called technology brokers, as their advantage (and role) is in their ability to build connections across a wide range of disparate domains and organize solutions that combine resources across them.[4]

Like the mass production techniques that enabled the Model T, the breakthrough products and systems that will propel fuel cells and other clean energy innovations to widespread use will also be built from the pieces of existing technologies. Like Ford’s mass production and the Model T, breakthroughs in fuel cell technologies will require a co-evolution of hydrogen production and use models that begin slowly by exploiting existing technologies yet build on each other to cross industry boundaries. And like Henry Ford and his organization, these breakthroughs will likely come from entrepreneurs who are in position to see how the technologies of a range of other domains might be brought together to create effective and successful new ventures in any one.

2.2 THE EVOLUTIONARY IMPACTS OF REVOLUTIONARY TECHNOLOGIES

The second characteristic that supports new ventures advancing emerging technology reflects the relative fit of the venture with the existing market structure and consumer dynamics. Technical advances alone are not enough to trigger rapid adoption. The revolution depends upon the slow accumulation and maturation of complementary technologies (whose recombination brings about new and innovative capabilities), but it also depends upon the details through which they are ultimately introduced: the design of the new venture.[5]

Design represents the particular arrangement of concrete details that give form to new products and processes. While we tend to talk about technologies in the abstract—the Internet, genetic cloning, and the automobile—the public (ourselves included) first meet and adopt these technologies in very concrete forms—Netscape and Yahoo, Dolly the Sheep, the Model T. This includes the look and feel of a new product, but also its particular choice of performance attributes, of legal and financial structures, of social connections that embed it within existing systems, and many other choices—some conscious and some not. Successful designs, from Edison’s electric light to IBM’s first general purpose computer, found ways to turn revolutionary technologies into initially evolutionary changes in market dynamics and consumer behaviors.[6]

While the role of design can be seen in modern attempts to introduce new technologies, its role is perhaps most clear in another of our most iconic technological revolutions, Edison’s system of elec-

Edison and the Design of the Electric Light: A Case Study

From where we are today, is there any question of electricity's ability to overthrow gas lighting? In 1882, gas jets provided a sputtering, yellowish flame equal to a 12W bulb. Smoke from the lamps scarred walls and paintings, and risked fire. Acids associated with the gas dangerously eroded the rubber and leather diaphragms of lamps. Electric lighting promised a brighter, cleaner light at a lower cost and these benefits became visible as arc-lights began lighting the streets, bridges, and parks of U.S. cities.

At the time, gas companies enjoyed monopoly pricing and profits. Gas lighting first appeared on city streets in 1825. By 1878, gas companies were worth $1.5 billion across the US, and were deeply entrenched in the social, political, economic, and physical infrastructure of cities. In New York, gas mains crossed the city underground, the city employed an extensive corps of lamp-lighters, and gas companies wielded powerful influence over the city aldermen and the mayor (Tammany Hall). When Edison introduced his innovation, the gas industry was as entrenched as any business interest we might find today. These institutions would not go softly into the dark night.

And the reality of the early electric light was confusing and messy. In the words of Britain's leading scientists, Edison's ideas demonstrated "the most airy ignorance of the fundamental principles both of electricity and dynamics." In the early years, brown-outs and black-outs were a common occurrence. Adopting electric light meant ripping up floors and walls to run wiring throughout, yet few qualified laborers existed with the skill to wire buildings for electricity. Sparking from circuits and poor wiring caused frequent fires, and falling wires and wet streets shocked pedestrians and horses alike. A month after the Pearl Street Station opened, New York's gas companies began a price war that would make electricity the far more expensive alternative. Finally, in 1886, the battle between Edison and Westinghouse over DC versus AC electricity publicized the dangers of electrocution with headlines like "Electric wire slaughter."

So why do we remember Edison and attribute the modern electric age to his actions?

Despite the fact that others had already developed (and patented) versions of the incandescent bulb, and despite the presence of arc-lighting and other systems of electric lighting, Edison succeeded in turning an emerging technology into a widely adopted system that displaced the existing gas lighting industry. And he did so in surprising ways.

Edison the visionary saw a world powered by electricity:

> ***The same wire that brings you light will also bring power and heat–with the power you can run an elevator, a sewing machine, or any other mechanical contrivance, and by means of heat you may cook your food.***

And from a perspective of innovation, Edison built a better mousetrap.

Yet he chose to embed his innovation within–rather than distinguish it from–the existing institutional environment. Edison the pragmatist designed a system that accounted for market realities--the existing understandings and behaviors surrounding gas lighting.

> ***To effect exact imitation of all done by gas so as to replace lighting by gas with lighting by electricity...not to make a large light or a blinding light but a small light having the mildness of gas.***

Rather than offer the public a product and system that differentiated electricity from the incumbent technology, he went to great lengths to fit the new technology as cleanly as possible into the existing market structures and consumer behaviors surrounding gas lighting. He presented a 13W bulb, despite having a 40W bulb burning in his lab. He presented a central generating plant, despite a profitable

— continued on next page —

Edison and the Design of the Electric Light CONTINUED

business selling isolated electric systems (and DC electricity). He buried his mains underground, despite lacking adequate insulation. He charged by meters despite lacking a meter for the first 6 months. And, for 10 years, having a meter that froze in winter. He incorporated under gas statutes to allow him to dig in the city streets. He courted gas company investors (esp. J.P. Morgan) as investors in his own venture. And his greatest technical challenge, subdividing light, was an effort to replicate users' experience with gas lamps.

The question of whether electric light would inevitably displace gas lighting can be debated for their technical or economic merits, but there were electric lights burning 40 years before Edison introduced his particular system. Indeed, the streets of New York were already lit by arc lights (as would soon be the Brooklyn Bridge) when Edison introduced his system. The revolution may have been inevitable, but it was also awaiting the right combination of existing elements—and the right design—that would enable the public to quickly understand the novel technology and easily assimilate it into their existing lives.

tric lighting. What to many seems a simple story of clean and safe electric lighting replacing dim and dangerous gas lamps was in reality confusing and messy and not a little bit uncomfortable. The electric light was, as noted earlier, on the scene for almost 80 years before Edison introduced his system in 1882 (the incandescent bulb was, by then, 40 years old). Yet even by the time Edison introduced his system, electricity was neither cheaper nor demonstrably safer than gas. So how is it that we remember Edison and the Pearl Street Station? We remember Edison because his venture, and its particular design strategy, enabled him to successfully gain rapid and widespread acceptance for electric lighting where others had not (see the accompanying case study: Edison and the Design of the Electric Light).

Despite envisioning an electrified world that would do many futurists proud, Edison's design strategy selectively chose which elements of his new system to present as novel and distinct and, as importantly, which to present as old and familiar, and which to hide from view altogether. Indeed, he and his team hobbled the initial performance of his system in order to couch it in the many familiar institutions of the established gas industry. By doing so, Edison designed a technological innovation that was technological revolutionary but in most other ways required only an evolutionary change in market dynamics and consumer behaviors.

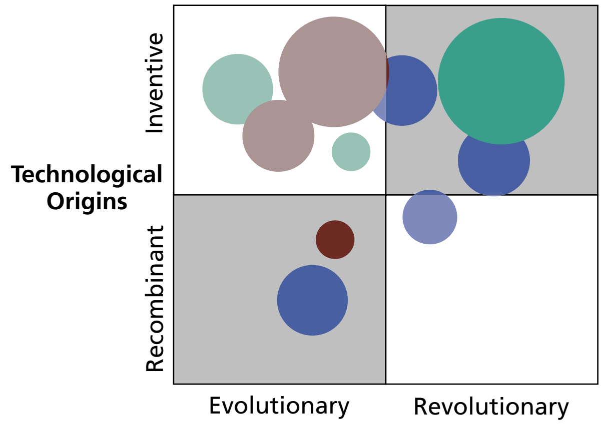
The biggest challenge for fuel cell research and development lies in identifying the best path for commercial ventures that will enable the initial adoption and ultimate diffusion of the technology. Visionary applications, like the Hypercar and Hydrogen Highway, provide useful attention and long-term goals, but as Alfred Marshal was fond of saying, "Nature does not make leaps," and neither do large, embedded socio-technical systems. The existing market structures and consumer dynamics cannot change to rapidly accept these new technologies. Instead, the first (and most critical) applications for fuel cells will have to present themselves as evolutionary changes in market and consumer behaviors. Placing fuel cells in forklifts and similar equipment, as Ballard Power System and Hydrogenics are attempting, represents such an approach—identify and pursue those initial markets where the performance attributes of fuel cells provide unique advantages over existing ICE and battery technologies and where the new technology requires small and manageable changes in markets and use.

2.3 UNDERSTANDING THE RELATIONSHIP BETWEEN ORIGINS AND IMPACT

This relationship between the maturity of an innovation and the extent of its market disruption can be framed as the research and development matrix shown in Figure 2. The vertical axis measures the extent to which a new technology derives from components of existing ones, ranging from recombinations of technical elements that are already in use elsewhere to elements that are just now emerging from laboratory work and have yet to be tested in real markets and uses. The horizontal axis represents the extent to which the successful adoption of an innovation requires fundamental changes in the structures of existing markets and patterns of consumer behavior. This matrix offers a means for evaluating the research portfolio of a given technology—for example the current efforts underway for hydrogen fuel cells, wind, or solar energy.

Arranged on this matrix, research and development efforts are typically bunched in the upper right quadrant, where science presumably gives rise to new technologies that carry the potential to radically disrupt current economic and social systems. This is a result, in part, of the need for bold and dramatic visions to secure funding but also because of the lingering belief that the next technological revolution will come from inventions and easily overturn the existing order. This quadrant reflects the utopian visions that drive many well-intentioned efforts to have science lead social change, and yet it also carries the almost insurmountable risks associated with utopian visions—the coincidence of technical and social change at some point in the distant future.

FIGURE 1 **Evaluating Project Portfolios Along the R&D Matrix**



History, on the other hand, suggests that most technology transitions originate in work conducted in the bottom left quadrant—which builds on existing technologies (and their supporting infrastructures) and first enters the markets requiring relatively little change in markets structures or consumer behaviors—thus encountering relatively few obstacles to initial adoption and use. Ford's adaptation of existing manufacturing techniques, and Edison's adaptation of the technologies of the telegraph, gas, and arc-lighting industries enabled each to spark technological revolutions.

More recently, pharmaceutical firms, while trumpeting their large investments in basic research, find many of their most effective products are the result of recombinations of existing work: Coumadin, the effective anti-coagulant, was developed directly from Warfarin, the rat poison, which itself was discovered as the toxic byproduct of a mold that grew on sweet-clover; bisphosphonates were used by plumbers to clear calcium in pipes before being adapted as a whitening additive for toothpaste and now as a treatment for osteoporosis (it is also being adapted to help fight cancers); and Viagra was a failed heart medication, re-combined to address another market.[7]

This is not to suggest basic research has no place in advancing new clean energy or pharmaceutical treatments, but rather that basic science produces results—but those results are rarely the ones intended. The revolution, when it arrives, often comes through a co-evolutionary process in which technological advances take place in use as market and consumer behaviors adapt to the differing features allowed by an existing technology borrowed from elsewhere.

3.0 PROVOCATIVE IMPLICATIONS

Anyone seeking to replicate the success of Edison's electric revolution or Ford's manufacturing revolution must recognize that technical feasibility or economic reasoning alone will not ensure an innovation ever achieves widespread adoption. Careful attention must be devoted to exploiting, through novel combinations, existing technologies and their supporting infrastructures, and to discovering the right designs for the actual products and ventures that the public will embrace. The critical roles of recombinant innovation and design in past technology transitions offer a number of implications for current efforts to research, develop, and promote hydrogen fuel cell technology.

3.1 MINDING THE GAP

To date, efforts to direct and develop alternative clean energy technologies have taken place largely within the domains of science and social policy. The need exists for better research aimed at effecting change through commercial ventures. Successful technological transitions often reflect accommodations for technological pragmatism—combining extant elements rather than inventing new ones—and for market realities—addressing current market and consumer needs rather than overturning them. Long-term research plays a powerful role guiding near-term efforts and galvanizing significant research investments. However, realizing any changes from these investments requires crossing the gap between technical possibilities and commercial applications. Some portion of current investments in clean energy research should be devoted towards understanding and evaluating these gaps, looking for the best paths to commercialization.

Such research, focused as it is on near-term technical and market realities, falls within the domain of innovation and entrepreneurship and new business development, research fields and perspectives not traditionally applied to the management of science. To be effective, then, some portion of research investments should be devoted to interdisciplinary work involving science, engineering, and business development. Global gains in efficiencies—particularly in self-organized systems (like free markets)—can only be achieved along paths that ensure local gains for participants. While science and engineering research is well-suited to addressing system-level issues, research in business development and entrepreneurship is well-suited to address the creation of local incentives for change.

3.2 EARLY COMMERCIALIZATION OF NICHE APPLICATIONS

The overwhelming image of fuel cell technology is as a replacement for the internal combustion engine (ICE), yet the automotive market is one of the largest and most complex socio-technical systems in place. Early commercialization of niche applications outside the automotive market can build valuable infrastructure and provide essential learning-by-doing that will shape the subsequent path of larger scale applications for hydrogen fuel cells. These niche applications are for markets where the fuel cell's current performance attributes (i.e., clean power, independence from the grid, security) offer clear—and profitable—advantages to potential customers. Research focused on the near-term introduction of such commercial ventures—guided by existing scientific models yet exploiting existing technologies—may better affect technology transitions than additional long-term research.

New technologies first enter markets by underperforming established technologies for traditional uses—the fuel cell fares poorly against the ICE in automotive markets, and poorly against the grid in electricity markets. But new technologies also typically increase in performance until they meet and exceed existing customer expectations, at which point incumbent technologies and organizations lose their strategic advantage. Importantly, however, while emerging technologies appear to under-perform existing technologies—for example the hydrogen fuel cell vehicle relative to the ICE—this comparison oversimplifies the definition of "performance" and hinders the recognition of alternative and valuable attributes not previously addressed by the existing technology.

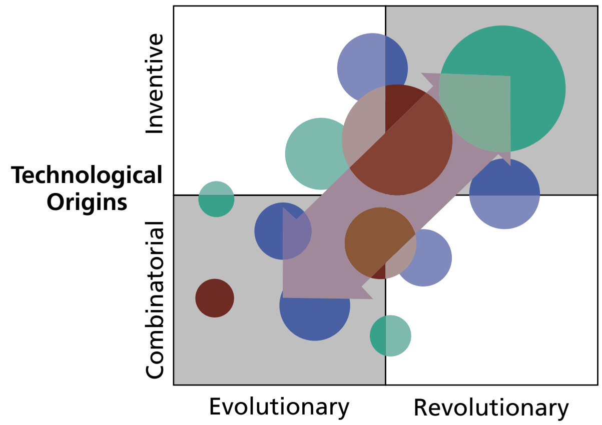
Emerging technologies exploit, and often give rise to, new values and use patterns not previously enabled by existing technologies (i.e., smaller disk drives both exploited and enabled portable computers). It is within these niche markets that new technologies such as fuel cells have opportunities to succeed. And yet even niche markets represent significant challenges. One of the performance advantages of fuel cells—reliable backup power—faces a unique difficulty because the best customers are also the most wary of a new technology with no track record. The challenges in these markets, while significant, are considerably less than exist in the automotive market. New ventures in these markets are more likely to succeed, and thus more likely to build commercial infrastructure and provide learning-by-doing in ways that additional research in larger markets cannot. So while hydrogen fuel cell research and development may be guided by visions of displacing ICEs in automobiles, the elements necessary to enable that revolution must first be built in alternative markets and applications and not in direct competition with commodity power or ICEs.

3.3 SHIFTING THE RESEARCH PORTFOLIO BALANCE

The research and development matrix provides not only a means to evaluate the technical and market characteristics of an emerging technology, but also a means for evaluating the fit between the overall portfolio of investments currently underway and the strategic goals of the sponsoring organizations. A balanced research portfolio would include both long-term research efforts and near-term commercialization efforts (see Figure 3). Recalling the matrix, projects in the upper right quadrant reflect a few, expensive bets on technical uncertainty but hold the potential for dramatic social change—for example, the application of fuel cells to transportation. The lower left quadrant, on the other hand, reflects many small bets on more realistic and near-term technological innovations and relies on evolution-in-use to achieve changes in market and consumer behaviors—for example, the application of fuel cells to (relatively) stationary power.

As described previously, projects in the upper left quadrant represent significant technical risk but offer relatively little potential evolution in market structures and consumer behaviors, while projects in the lower right quadrant, despite their technical feasibility, may require too dramatic changes in behavior to gain a foothold in the market. These projects should be revisited to consider how new business models can reduce their technical risk (by switching to existing technologies) or reduce their market risk (by exploiting existing market and consumer dynamics).

FIGURE 3 **A Diversified R&D Portfolio**

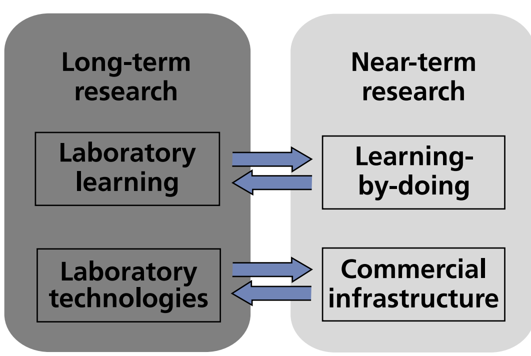


Overall, there is a need to strategically align and balance the research investments in Hydrogen fuel cells across state, federal, and private sources. The learning-by-doing that emerges from near-term research and commercialization efforts will complement and guide laboratory learning as much as laboratory learning supports application development. The challenge, however, lies in the gap in motivations between those who would fund basic research and those who would fund commercial ventures. Near-term research into commercial applications for fuel cells cannot provide the returns that the venture capital industry has come to expect (roughly 20% annual returns), nor can it clear the academic and political hurdles necessary for traditional research grants. An effective shift in the research portfolio requires an equivalent shift in how we attract and allocate funds for research.

3.4 TECHNOLOGY BROKERS TO FOSTER AND TAP THE DIVERSIFIED RESEARCH PORTFOLIO

Technology advances as science and practice co-evolve—laboratory learning shapes, and is shaped by learning in practice, and technologies developed in the lab are modified for industrial uses and are often built from existing industrial equipment (see Figure 4). Current clean energy research is conducted and funded through a wide variety of public and private agencies, laboratories, and geographic regions. Such diversity enables a range of approaches in the development of clean energy solutions, but only to the extent that key learning can ultimately be harnessed to create new combinations of the resulting technological advances. Regional research clusters galvanize local investments and provide strong supporting infrastructures. However, the resulting balkanization of research efforts, visions, and outcomes may result in inefficiencies if no agencies take responsibility for acting as brokers between these different domains.

FIGURE 4 **The Learning Relationship Between Labratory and Practice**



Such brokers have played prominent roles in past commercial innovations. They have also served useful roles in working between research programs and the marketplace. Some successful programs include the Canadian Health Services Foundation, which both acts in a brokering capacity to link otherwise different hospital systems across Canada and works to support the development of individual brokers who can carry out similar efforts at the local levels and the Cooperative Research Centre for Freshwater Ecology in Australia, which links researchers and land-use planners around critical issues in freshwater management.

A similar role in bridging between the disparate federal, state, and local efforts to develop fuel cell solutions may provide similarly valuable results. For instance, such brokers can pool resources to acquire common, shared resources. They can also connect the research and commercialization efforts underway in the relatively disconnected work of hydrogen production and consumption technologies.

The Public Fuel Cell Alliance represents one organization that is well-positioned to help connect and coordinate disparate research findings, as well as share the learning-by-doing that derives from early commercialization efforts across the country and globe. Such connection and coordination would entail hosting conferences and workshops across state and national research programs and across local and global commercial ventures. Additionally, such an organization is well-positioned to act as a central clearinghouse for activities, technologies, and human resources that could be effectively shared in the development of a robust and widespread hydrogen fuel cell industry.

4.0 CONCLUSION

The relationship between science, social policy, and technological change is complex and rarely flows in expected directions. New technologies lead changes in social policies and science more often than they are led, and attempts to use social policy to drive science to drive technological change requires fighting the prevailing currents. Such endeavors are not impossible, but they do require a better understanding of how change takes place and how to identify the best paths to commercialization. The preceding discussion was intended to bring lessons from past technology transitions to bear on the pursuit of new and potentially revolutionary technologies like hydrogen fuel cells.

ENDNOTES

1 The quote is also misleading because Emerson didn't actually say those words. Emerson originally said "if a man has good corn, or wood, or boards, or pigs, to sell…you will find a broad, hard-beaten road to his house." Emerson was not talking about innovation, but simply about selling a good product. And when you think about it, even a better mousetrap is really not about revolutionary innovation but rather about incrementally improving something with which the public was already quite familiar. And yet these words have come to mean success will embrace whoever manages to develop a better way of doing things. The now ubiquitous version originated some seven years after Emerson's death as a result of a journalist's creative editing.

2 Nathan Rosenberg (1982) provides an invaluable resource for those attempting to understand the economic histories of large-scale technological changes. One of Rosenberg's more relevant findings is that the impacts of technological innovations are more likely to be felt outside the industries which those technologies first emerged, as the people, ideas, and artifacts migrated to other industries and applications. Rosenberg, N. (1982). *Inside the Black Box.* New York, Cambridge University Press.

3 John Steele Gordon, The Business of America (2001, Walker & Company).

4 I have written extensively on the role of technology brokering in large- and small-scale innovation in How Breakthroughs Happen: The Surprising Truth about How Companies Innovate (2003, Harvard Business School Press).

5 Tushman and Anderson (1986) introduced the concept of punctuated equilibrium to the study of technological innovations. Studying the introduction of innovations in industries, they found evidence that technological transitions took place as brief moments of disruption and dramatic productivity improvements followed by longer periods of relative calm and incremental changes. Tushman, M. L. and P. Anderson (1986). "Technological Discontinuties and Organizational Environments." *Administrative Science Quarterly* 31: 439-465.

6 For more detailed examinations of these cases, see J. Yates, and A.B. Hargadon and Y. Douglas, "When Innovations meet Institutions: Edison and the design of the electric light" (*Administrative Science Quarterly*, 2001).

7 Another powerful example is the evolution of the personal computer operating system. In 1968, Doug Engelbart first introduced a graphical computer interface, with mouse, pull-down windows, and point-and-click navigation. However, the computer industry was more concerned with advanced research in artificial intelligence and office automation, and his novel technology was all but ignored. Over the next decade, researchers at Xerox PARC integrated Engelbarts ideas into their pioneering work on personal computing, but were ignored within Xerox. Finally, Steve Jobs and Apple computer incorporated the ideas, in 1984, in the Macintosh personal computer but it wasn't until 1995 that Microsoft's Windows achieved widespread diffusion and use.

8 Interestingly, Starr's original patent, in 1846, was rejected because it was not seen as anything new, and the commercial production of incandescent bulbs was infeasible.