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*Illustration by Harry Campbell*

Unless clean tech follows well-established rules of innovation and commercialization, the industry's promise to provide sustainable sources of energy will fail.

On April 22, 2009, four months after he took office, President Barack Obama proclaimed that green technologies would be the linchpin of economic advancement. "We can hand over the jobs of the 21st century to our competitors," he said at a wind energy manufacturing plant in Newton, Iowa, "or we can confront what countries in Europe and Asia have already recognized as both a challenge and an opportunity: The nation that leads the world in creating new energy sources will be the nation that leads the 21st-century global economy."

Private sector investors in the United States have been similarly enthusiastic, investing a total of $8.9 billion in clean energy companies in 2009.[1] This is a sizable sum, but it does not guarantee that green technologies will provide a sufficient return on investment. Both the public and private sectors spent billions of dollars developing the market for corn-based ethanol over the past 20 years before a consensus emerged that ethanol would not solve the economic and environmental problems it targeted.

A similar story may be playing out in the solar cell industry, as evidenced by Massachusetts's experience with Evergreen Solar. In 2007, the state invested millions of dollars to entice Evergreen to build a new plant near Boston. The plant did create 800 manufacturing jobs, but the excitement over the deal eventually soured. As solar cell prices plummeted from late 2008 onward, Evergreen faced mounting losses and saw its stock price crater from $15 to 80 cents. Then in January 2011, Evergreen announced it would close its factory and shift production to a joint venture with a Chinese company in central China—this after $43 million in assistance from the government of Massachusetts.[2]

Massachusetts's experience should serve as a cautionary tale about investing in green energy. If governments pour large subsidies into green technologies, they run the risk of backing technologies that, like ethanol, are fundamentally flawed. Solar power is a similarly flawed technology if it is deployed in competition with the existing power grid.

We believe there is a better way to evaluate, invest in, and deploy green energy technology. Our research examines the drivers of successful innovation and illustrates how these drivers can yield a set of predictable rules that govern the success of new technologies. We also have developed a set of factors that predict the failure of a new technology. Green energy technologies, just like those that drive personal computers, mobile phones, and software, must follow the rules of innovation and avoid its pitfalls.

For our purposes, green energy technologies are those that either harness power from renewable, sustainable sources or

seek to reduce adverse human impact on the environment. Many of these technologies also hold the potential to contribute to energy independence. We include such technologies as solar, wind, and geothermal power, biofuels, and smart power grids, as well as hydrogen and electric vehicle propulsion. In order for these new sources of energy to have the widest possible implementation, investors, technologists, and policymakers must understand not just their potential impact but also their commercial viability. Many technologies can be successful if they are deployed according to sound innovation theory.

## *Why Advanced Technologies Often Fail*

There are generally four reasons that advanced technologies fail to achieve commercial success: technical challenges, systemic complexity, head-on competition, and because customers don't want it.

***Technical Challenges*** | The first reason is obvious: The technological approach itself proves to be unworkable or unscalable. The plasmodium parasites that cause malaria, for example, evolve so quickly they have defied eradication by conventional immunological techniques. And similarly, the potential for generating energy from controlled nuclear fusion is still far away, because technological problems repeatedly defy techniques to initiate and control this reaction.

Most green energy technologies face some kind of significant technological hurdle. Solar cell technology has undoubtedly advanced, but it still faces technological hurdles to improving efficiency. Similarly, battery technology, which is critical for electric vehicles, is coming up against natural chemical boundaries. Fuel cells, elements of the smart grid, and wind turbines all run into technological problems.

***Systemic Complexity*** | A second reason promising technologies fail is that they are rarely "plug compatible" with existing value chains. Hydrogen-powered fuel cells promise a means of powering vehicles with no emissions except a trickle of water out the tail pipe. But fuel cells face an extremely long and challenging road to commercial acceptance, as they suffer from extraordinary systemic complexity. The ubiquity of the gasoline filling station is one reason that fuel cells will have a difficult time achieving widespread adoption. The infrastructure required to refuel a hydrogen-powered car does not exist and would require the coordinated investment of billions of dollars. Existing gasoline station equipment cannot be adapted to store and dispense hydrogen. This entire stock of equipment would need to be replaced. Hydrogen-powered cars can catch on only if hydrogen filling stations are liberally sprinkled across our roadways. Unfortunately, such stations will not exist unless there are a lot of hydrogen-powered cars as well. It is a classic technological chicken-and-egg problem that can be overcome only through expensive government mandates and subsidies that would alter the fuel distribution infrastructure in a coordinated way. With such a large and thriving gasoline ecosystem in place, we are more likely to see adoption in technologies that either work with the existing system or bypass it entirely. Gas-electric and plug-in hybrid vehicles are examples of technologies that improve fuel efficiency while working within the constraints of the existing infrastructure.

The refueling station problem is a well-known barrier to hydrogen adoption, but the systemic problems associated with hydrogen production may be even more troubling. Hydrogen does not naturally exist on the earth in the form required for fuel cells. Ironically, the most common form of producing it is to separate hydrogen molecules from natural gas, which produces harmful carbon emissions. The other option to produce pure hydrogen is through electrolysis, which breaks down water into its constituent hydrogen and oxygen molecules. The problem with this method is that even if large-scale electrolyzers were technologically practical, such machines would require large quantities of electricity. With renewable electricity generation still limited, the only cost-effective way to power an electrolyzer would be from fossil fuels, again defeating the purpose of hydrogen-powered vehicles.

Without sufficient capacity of renewable electricity generation, hydrogen-powered vehicles will not solve any environmental problems. For fuel cells to make sense, the entire system of electricity generation must be substantially modified. And perhaps even more daunting: Should this feat be accomplished, *every subsequent step* in the value chain would require a wholesale redesign of its existing infrastructure. We are quite certain hydrogen fuel cells will find limited success in displacing gasoline-powered engines.

***Head-On Competition*** | The third cause of the commercial failure of advanced technologies is head-on competition with established technologies. When a technology is forced into direct competition against an established foe, it will be adopted only if it is more cost- and performance-effective than the established technology in the markets where it is being used. This creates enormous barriers against commercial success. New technologies have much better success rates when they are aimed initially at nonconsumers—those who are not consuming the existing products or services because of lack of wealth, expertise, or access. These nonconsumers often embrace products with limited functionality or quality, because they are superior to the alternative: no product at all.

Consider the path that the transistor took in overthrowing the vacuum tube. Throughout the early 1950s, most electronics products were made with vacuum tubes—devices the size of a child's fist that consumed a lot of power. The mass of these devices meant that the televisions and radios from which they were built had to be large. Radios were placed on tabletops and televisions stood on the floor. All of the vacuum tube companies—the giants of consumer electronics, such as RCA, Zenith, General Electric (GE), and Westinghouse—saw the potential of the transistor and spent hundreds of millions (in today's dollars) trying to make the transistors good enough for the markets where vacuum tubes were used.

Meanwhile, some inventors saw the potential for transistors to create new markets altogether. The first commercial application for

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transistors was the germanium transistor hearing aid in 1951—an application where vacuum tubes weren't feasible. Then in 1955 Sony introduced its first pocket radio, a simple, inexpensive, low-performance product. But Sony marketed its radio to teenagers, customers who were delighted to have a limited product because it was better than the alternative: no radio at all. While the vacuum tube companies continued to work on the technology, Sony introduced the world's first portable transistor television in 1959. Again, it was a limited product. But by making a TV so much more affordable, a new population of customers whose apartments or wallets were not big enough to afford an RCA television now could have one. Again, because the simple Sony product was better than nothing, customers were delighted. New markets emerged as Sony wielded simplicity and affordability to compete against nonconsumption. By the late 1960s, solid-state technology had become good enough that Sony and Panasonic could begin building large televisions and radios. Within about five years, customers had switched over to solid-state electronics, and every one of the vacuum tube businesses vaporized.

Solar and wind power generation are green technologies that, at least in the developed world, are being deployed in competition with the existing electrical grid. As noted, whenever new technologies compete head-on with established systems, challenges loom due to the cost and performance gaps between the new technology and the old. Solar and wind power are no different. Both are more expensive than the existing grid, and both have performance deficiencies related to weather conditions. Even with significant government subsidies to encourage adoption, the percentage of total electricity derived from wind and solar in the United States remains tiny, illustrating the barriers these technologies face to displacing the existing grid.

***Customers Don't Want It*** | The fourth reason promising technologies fail commercially is that, although they provide technically sophisticated functionality, they do not help customers do a job they need to have done. By job, we mean a fundamental problem a customer needs to solve, including a specific result or outcome. If a technology helps users accomplish a job they are already trying to do in a superior way, it is far more likely to succeed. If a technology tries to solve a job with which a customer isn't terribly concerned, it is likely to face headwinds.

The rise of digital photography offers an illustration of how consumers will change their behavior in response to new technology, but not the fundamental job they are trying to do. When prints were the only way to view photos, people had the best of intentions to arrange photos in albums, but the vast majority of prints were viewed once, then placed in a shoebox. Despite this tendency, most people would ask for double prints so they could mail the best photos to a family member, not knowing beforehand which prints would turn out well. Once digital cameras were fully adopted, consumers changed their behavior, but not the fundamental job they wanted to perform with photos. Now, the killer app for photos is e-mail. Despite all the systems for online photo albums, the dominant consumer behavior is to attach photos to an e-mail for sharing. The technologies for online photo albums were always going to be challenged as they tried to perform a job that most consumers weren't trying to do. The challenge is not in changing consumer behavior, but in changing the job that consumers are trying to accomplish.

Although we believe the smart grid will be an important incremental innovation, certain aspects of it run afoul of the jobs-to-be-done concept. The term "smart grid" encompasses a set of technologies that allow both electricity producers and consumers to make better decisions about power use through real-time data. Portions of the smart grid system are necessary, evolutionary improvements to the existing power grid. For example, advanced smart meters benefit power companies by eliminating the need for manual meter reading, automating the billing process, and providing real-time detection of outages.[3] We believe smart grid technologies that lower cost or improve performance will be readily adopted by power companies.

But smart grid enthusiasts may be disappointed as they find that the behavioral change from consumers is not as strong as they had anticipated. A subset of smart grid technologies are intended to provide electricity users with price signals to help people manage their power consumption more efficiently. These technologies envision a home in which a consumer, seeing the high cost of electricity from 2 p.m. to 4 p.m. in the summer, will turn down his air conditioning, turn off lights, and lower the temperature in the fridge. The potential savings from this technology could be substantial—as much as 30 percent of a typical consumer's power bill.

Although smart grid technology makes it possible for consumers to achieve such savings, it does not ensure that consumers will change their behavior. Just as we saw in the photography example, consumers will change their behavior only if the technology helps them accomplish a job they were already trying to do. For frugal consumers who already monitor their power consumption to reduce their power bills, real-time price signals will be welcomed as a way to manage their bill more efficiently. Unfortunately, not all consumers fall into this category. Those who are not looking for a system to help manage electricity usage will probably have little interest in smart grid technologies. They will not change their behavior, because the technology does not help them do a job they already were trying to do.

Are green energy technologies doomed to failure for the reasons we've outlined? We don't think so. What follows are recommendations

## Rating Green Technologies for Successful Implementation

| | Low technical hurdles | Compatible with existing systems | Can win head-on competition with incumbent technologies | Fills customer "job-to-be-done" |
|---|---|---|---|---|
| Geothermal | ✔ | ✔ | ✔ | ✔ |
| Plug-in hybrid vehicles | ✔ | ✔ | | ✔ |
| Solar | | ✔ | | ✔ |
| Wind | | ✔ | | ✔ |
| Biofuels | ✔ | | | ✔ |
| Smart grid | ✔ | | ✔ | |
| Fuel cells | | | | ✔ |
| Electric vehicles | | ✔ | | |

Some of the most widely discussed green technologies face multiple barriers to commercialization. Technologies that avoid most of these barriers, such as geothermal power and plug-in hybrid vehicles, already have been or will be adopted commercially.

on how to develop and deploy green energy technology to maximize its chances for success in the developing and the developed world.

## *Green Energy in the Developing World*

Solar energy is both less reliable and more expensive than traditional power generation, despite its desirable environmental impact. Given its limitations, would-be commercializers of solar energy should ask themselves: Where are there customers who would value a technology that generates unreliable electricity? The answer: the rural villages of India, Mongolia, Indonesia, Tanzania, and other developing nations. These are the locations where solar energy can be successfully commercialized, because solar will be competing against nonconsumption of energy rather than a reliable, inexpensive power grid. Just as Sony's transistor radio gained acceptance among nonconsumers, green technologies will find enthusiastic reception in the unconnected villages of the developing world.

Commercializing green technology in the developing world has the added benefit of contributing to the fight against carbon emissions. Currently, nearly half of carbon dioxide emissions are from developing nations. According to the U.S. Department of Energy, by 2030 developing nations will produce nearly double the carbon dioxide emissions of developed countries if their energy sources develop along the same lines. So green technology can enable both greater energy consumption and a cleaner path to economic development.

Although competition with nonconsumption will greatly aid its commercial success, green technology faces unique challenges in the developing world. First, technologies succeed best when the business unit responsible for developing and deploying the technology is also located where its targeted customers are. That way, the business unit will have the cost structure and managerial incentives that make pursuing "good enough" products at lower price points an attractive proposition.[4] For example, when the management of GE's medical imaging business was largely located in the developed world, it focused on producing the most advanced and highest margin CT and MRI scanners possible. Once GE created an autonomous business unit in China, it was able to develop a low-cost ultrasound machine that had great benefits in rural China. Furthermore, as GE continued to develop these products, it began to find applications for them in the developed world, opening up large markets for its innovative products.

The second requirement for succeeding in the developing world is to sell a product that provides a full solution for a customer need. In the developing world, it may not be enough to sell solar panels. Such a product may be of little use to a village with no electrical infrastructure or appliances. Rather, it is important for companies to deploy a technology that is tied to an application. D.light design, which is based in India but was founded in Silicon Valley, illustrates the importance of understanding customers' circumstances. Rather than just offer a lamp in a place with unreliable energy or offer a raw solar cell, D.light bundles its lamps with solar panels fit for consumers' energy requirements, which are small—often around 0.5 watts. Their products are far better than commonly used kerosene alternatives, because they are significantly safer, are more durable, and provide far better light. D.light design has distributed 1.7 million lamps to rural Africa and India; it continues to develop its business.

The third requirement for the developing world is that companies may need to integrate their activities across a wider spectrum of the value chain. In many of these countries, a well-functioning sales and distribution infrastructure with wholesalers and retailers does not exist. As a result, companies that usually rely on partners to sell and distribute their product may find a similar strategy impossible in the developing world. In these regions, companies may need to take on sales and aftermarket servicing to develop their markets. One successful approach is the creation of a network of rural entrepreneurs who sell a company's products to friends and family. D.light design has developed such a system to increase its reach.

## *Green Energy in the Developed World*

Green energy adoption faces more daunting challenges in the developed world. With a convenient, low-cost, and pervasive energy infrastructure in place, green technologies must prove themselves more affordable or better performing to displace their competitors. By and large, the only way green energy has been able to meet that standard is through government subsidies that bridge the gap between actual cost and grid parity. Although a small segment of consumers actively seek renewable energy sources out of concern for the environment, the battle to win the hearts and minds of hundreds of millions of developed world consumers will not be won quickly enough to solve our energy and environmental problems. We believe that there are some spaces in which green energy technologies can succeed and thrive in the developed world, but they must comply with the rules of innovation.

One of the green technologies that can find a market is the electric vehicle (EV). The EV contains certain limitations that will prevent it from winning in head-on competition with traditional vehicles. Remember, to win in head-on competition, a technology must be either less expensive or better performing, and the electric vehicle is neither. Despite undeniable progress, no manufacturer has succeeded in bringing the cost of EVs below that of traditional sedans. And even if EVs reach cost parity with gas vehicles, their performance limitations remain. Battery technology caps an EV's range at 100 miles between recharges. Because a full recharge takes eight to 12 hours, EVs cannot be used for long trips, which make up an important part of the job-to-be-done for which consumers buy a car.[5] Furthermore, most EVs accelerate slowly and have maximum speeds well below the 80 mph that consumers typically demand.

We believe there is a set of customers who would actively seek out a car with both limited range and acceleration. The parents of American teenagers have precisely the job-to-be-done for which an electric vehicle would be a perfect match. These parents want to allow their teenagers to transport themselves to and from school, work, and friends' homes, but nowhere else. They would actually prefer a car that does not accelerate quickly or drive on freeways. To complete their appeal to this market segment, EVs need to be priced cheaply so that affluent families could plunk down cash to buy one. Again, this is good news for EV manufacturers, as they can offer a bare-bones version of their vehicles and not worry about their performance relative to standard sedans. Compounding the good news for manufacturers is the fact that by getting a product on the market, they will incrementally improve their EVs, slowly closing the performance gap with gas-powered vehicles. In this way, a low-priced EV could disrupt the predominance of the gas-powered vehicle, just as Sony's transistor radios disrupted vacuum tube radios.

Although a real market for low-cost electric vehicles exists, it is unlikely that EVs will achieve substantial market share for some time. Disruption often unfolds at a glacial pace, especially in an industry like autos with high capital costs and long design-to-production cycles. For that reason, the primary mode of competition in the auto industry will continue to be a sustaining one. By sustaining competition, we mean that competitors will continue to try to best each other within the framework of well-established technologies, incrementally improving performance or reducing costs.

In industries where sustaining competition dominates, hybrid technologies are likely to be adopted. This is because hybrid technology enables exactly those incremental performance or cost advantages that allow companies to win a head-on competition while remaining within existing systems of use. In the automotive industry, we have already seen hybrid vehicles, such as Toyota's Prius, make significant inroads as fuel efficiency becomes an increasingly important basis of sustaining competition. Such vehicles do not suffer from any of the problems of systemic complexity that hydrogen- or battery-powered vehicles face. They operate wholly within the existing automotive infrastructure, not requiring the infrastructure to bend to its needs. Hybrid vehicles also may compete very effectively in a head-on manner by being more convenient, if not eventually lower cost. Although current hybrid technology cannot yet win in head-on competition with gasoline vehicles, hybrids are far more likely to be adopted in head-on competition than are pure-play electric vehicles. We are particularly optimistic about the coming generation of plug-in hybrids, which will propel cars up to 40 miles on electricity before requiring the gasoline engine to kick in. This solution provides the vast majority of everyday driving needs on electricity alone, while preserving the flexibility to take longer trips. Early models will not be cost competitive, but as the technology improves and scale advantages arise, cost competitiveness may well be achieved, especially if gasoline prices continue to rise.

## *Conservation in the Developed World*

So long as green technologies follow the rules of successful innovation, they will be adopted readily in the developed world. The problem is that the developed world's existing energy infrastructure is so cheap and convenient that it creates large barriers to adopting new energy technologies. And with few nonconsumers of energy, they offer hardly any space in which green technologies can take hold organically. This is why governments in developed countries must play a large role in formulating and enforcing conservation mechanisms to reduce energy use.

The recent move by some governments to phase out the incandescent lightbulb is a good example of the kind of conservation measures that are required. The incandescent lightbulb traces its history back to Thomas Edison. These bulbs produce light by heating a filament until it glows inside a glass bulb. Although the technology has served the developed world well for more than a century, it is terribly inefficient in its use of energy. Up to 90 percent of all the energy used in a lightbulb is wasted as heat, with the bulb producing only 15 lumens per watt. By contrast, a compact fluorescent lightbulb (CFL) produces 50 to 100 lumens per watt, and the energy savings more than make up for a CFL's increased cost ($3 per bulb vs. 50 cents per bulb for incandescents). If a consumer were to spend $90 on 30 CFLs for her house, total energy savings could range from $440 to $1,500 for the five-year life of the bulbs.[6] The United States has now mandated that the incandescent lightbulb be phased out of the U.S. market in 2012. Experts have estimated that if everyone in the country switches to CFLs, it will eliminate the need for 30 coal-fired power plants, and will save an amount of electricity equivalent to that used by all the homes in Texas *each year*.[7]

Government-mandated conservation efforts succeed best when they align with the interests of entrenched stakeholders. In the case of the lightbulb, manufacturers find the mandate attractive as CFLs represent a higher priced, higher profit margin product than incandescent bulbs. Consumers also stand to benefit from the energy savings reaped from CFLs. By contrast, California's attempt to establish quotas for electric vehicles in the early 1990s was challenged from the beginning. As the quotas applied only to California and EV technology was so expensive at the time, it would have been very difficult for automakers to earn a profit on vehicles produced in such low quantities. This ran counter to their natural interest to produce higher volume, higher margin vehicles. The resulting industry opposition eventually caused California to retreat from its proposal. We don't argue that government should cater to powerful interests, only that it should be prepared for a much more difficult path if conservation mandates create large burdens for industry.

It is undeniable that the world needs cleaner and more sustainable sources of energy, and green energy technologies can contribute to that effort. Yet our research into innovation and technology commercialization cautions us that the development and success of these technologies must conform to well-established rules. It would be a mistake for governments to pour large sums of money into technologies that will have difficulty finding commercial acceptance. But that is precisely the path many governments appear to be following. A better way to develop and deploy green energy technologies is to incubate them in places where they can succeed commercially from the outset. ■

*Notes*

1 Ernst & Young, "Venture Capital 2009 Investments in Cleantech Fall 50% to $2.6B as Investors Shift Focus to Energy Efficiency," Feb. 8, 2010.

2 Keith Bradsher, "Solar Panel Maker Moves Work to China," *The New York Times*, Jan. 14, 2011.

3 Michael McNamara, et al., "Clean Technology Primer," Jefferies & Company Research, Sept. 2009.

4 These institutional dynamics are more fully documented by Jeffrey Immelt et al., "How GE Is Disrupting Itself," *Harvard Business Review*, October 2009.

5 Shai Agassi's EV service provider company, Better Place, attempts to solve this problem through its network of battery switching stations, but this effort suffers from significant upfront capital costs.

6 Marianne Lavelle, "FAQ: The End of the Light Bulb as We Know It," *U.S. News & World Report*, Dec. 19, 2007.

7 Steve Hargreaves, "The Fluorescent Light Bulb Boogeyman," CNNMoney.com, Sept. 3, 2009.