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Unlocking Clean Energy

Many government policies now "lock in" mature clean energy technologies while blocking out innovative alternatives. Here's a plan to transform lock-in barriers into bridges for technological succession.

Confronting climate change will require transforming the world's energy systems to slash their greenhouse gas emissions. Although temperatures continue to rise at an alarming rate, some observers argue that increasing global investment in clean energy signals progress. But gushing investment flows to deploy existing clean energy technologies obscure a discouraging countercurrent: investment in new, innovative technologies has slowed to a trickle. For example, investors around the world spent nearly $300 billion in 2015 to deploy clean energy technologies that already exist, more than tripling annual investment from a decade ago. But between just 2011 and 2015, venture capital (VC) investment in companies developing new clean energy technologies fell by more than 70% to less than $2 billion. Silicon Valley VCs, having lost over half their money from a flurry of failed investments between 2006 and 2011, remain reluctant to invest in clean energy technologies that do not resemble software apps.

This is alarming. Advanced technologies—including energy-dense batteries, safer nuclear reactors, and dirt-cheap solar materials—will be essential to a low-carbon transition that avoids slowing the world economy while proceeding at the scale and speed required to confront climate change. But the widening investment gap between deployment and innovation endangers prospects for improving the performance and reducing the cost of clean energy. And by overemphasizing deployment, policy makers can tilt the playing field against emerging technologies, which are at a disadvantage to begin with. Because commercially mature clean energy technologies get incrementally better as producers and users gain experience with them, policies that favor technologies available today may erect barriers to market entry for advanced technologies tomorrow.

The result is "technological lock-in," a syndrome endemic to markets in which the next technology generation cannot replace the existing one. Nuclear power provides a clear example of such lock-in. The prevalence of light-water reactors (LWRs) today, largely a result of United States military and regulatory policy favoring that particular design, poses nearly insurmountable entry barriers to next-generation nuclear designs that could offer safety, cost, and performance advantages. Three other clean energy "platforms," or technological categories—biofuels, solar photovoltaic power, and batteries—are at risk of succumbing to lock-in. In these platforms, new technologies face economic barriers to competing with incumbent clean energy technologies, an uphill battle that is exacerbated by public policy.

But two other platforms—wind power and efficient lighting—exhibit healthy technological succession rather than lock-in. And these success stories can inform public policies that mitigate, rather than exacerbate, the risk of technological lock-in.

Causes and consequences of lock-in

Economists have long known about technology lock-in. The first step toward lock-in is the emergence in the market of a "dominant design," a technology that captures a majority market share and becomes the incumbent technology. For example, almost every car made in the past century has run on an internal combustion engine (ICE), the dominant design for vehicle propulsion. Dominant designs can emerge for a variety of reasons unrelated to technological merits. In the engine example, neither the steam engine nor ICE was clearly superior in the early twentieth century. But then hoof-and-mouth disease led New England authorities to eliminate the watering troughs that horses and steam engine vehicles alike used, a chance event that helped put steam engines at a disadvantage. Similarly, even though early ICE-powered vehicles were fouler, noisier, and more dangerous than electric vehicles, ICE firms made the shrewd business decision to sell their vehicles as consumer products rather than offer taxi services, and they benefited from existing distribution systems for petroleum products. After racing to a quick lead, the ICE did not look back for the next century.

Once a dominant design emerges, firms that produce it can entrench their market positions through scale. As they increase production, they can improve the performance and decrease the cost of products—for example, through production economies of scale and "learning-by-doing." And as firms sell products to a growing market, increased adoption can drive down the costs of using the product and increase its value—for example, through network effects. These economic benefits create barriers to entry to firms marketing new technologies, which do not have the benefit of scale.

As a market matures and firms producing a dominant design grow, those firms may not invest much in research and development (R&D) to create fundamentally new products, because a substantial fraction of the benefits from R&D are "spillover benefits." R&D investment by one firm may, for example, advance scientific knowledge that other firms can then leverage. Therefore, these benefits are externalities from the perspective of a firm sponsoring R&D. As a result, private industries will often underinvest in R&D, instead investing in incremental process innovation that fortifies the incumbency of mature technologies.

One might conclude that government intervention is the answer, perhaps by filling the R&D investment gap left by the private sector. But often, government intervention can actually distort markets even more, further tilting the playing field toward incumbent technologies.

For example, governments may enact regulations that are tailored to the characteristics of an existing technology, often following the emergence of a dominant design. Intentionally or not, this bespoke regulatory structure can disfavor new technologies around which the regulations were not designed. As a case in point, in 1937, New York City implemented a system of requiring taxi drivers to purchase medallions, which authorized drivers to transport passengers, as a quality control measure. This decision did not forecast the recent rise of car-sharing mobile apps, such as Uber, and, as a result, the regulatory framework disadvantages a new, and arguably superior, technology that achieves quality control through user reviews.

Public policy can also obstruct new technology adoption by providing subsidies and other incentives to mature technologies, raising the entry barrier that natural economic forces already help erect. Policy makers may intend for their policies to be technology-neutral, but even a neutral policy can implicitly support existing technologies at the expense of

Land Art Generator Initiative *Powering Places*

The Land Art Generator Initiative's (LAGI) 2016 competition, *Powering Places*, invited artists, designers, scientists, engineers, and others from around the world to submit proposals for large-scale and site-specific public art installations that generate carbon-neutral electricity and/or drinking water for the city of Santa Monica, California. The 2016 design site offered participating teams the opportunity to use wave and tidal energies as well as wind, solar, and other renewable energy technologies.

Now more than ever, energy and water are intertwined. As California faces severe water shortages in the coming years, the amount of energy required for water production and transmission will increase. For this reason, LAGI 2016 expanded its definition of sustainable infrastructure artwork to include proposals that produce drinking water as well as clean electricity.

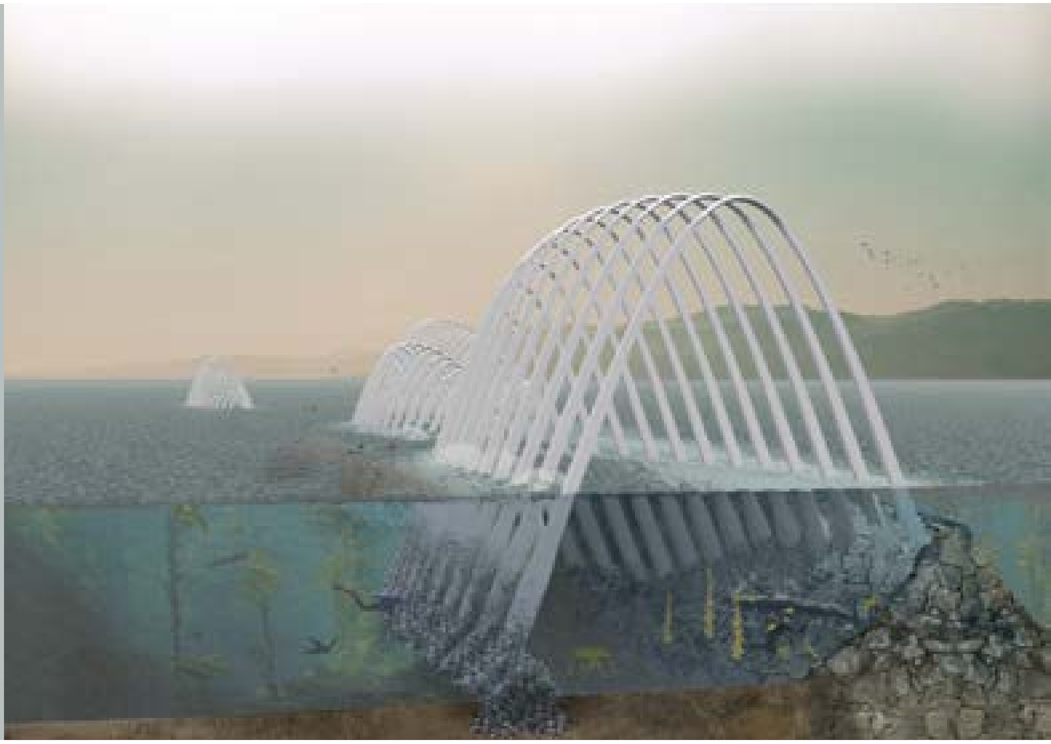
LAGI 2016 fits into the context of the efforts being made in Santa Monica and throughout Southern California to increase efficiency of water consumption and to harvest water sustainably. For example, the Santa Monica Pier is currently investigating ways to drastically reduce the use of potable water on site by innovations such as the use of recycled seawater for toilet flushing.

An exhibition of the winning design ideas was on view at the Annenberg Community Beach House in Santa Monica from October 4 through November 1, 2016. For more information about the winners and finalists, visit http://landartgenerator.org/competition2016.html.

emerging ones. This is the case for policies around the world that support renewable energy, including "feed-in" tariffs that compensate renewable power generation at a premium rate and standards that require utilities to obtain a certain percentage of their power from renewable energy. Because mature technologies can be rapidly deployed to take advantage of such policies, they can crowd out less mature technologies. This effect is pronounced when mature and emerging technologies compete for a cordoned-off market with limited capacity, in which deployment of one comes at the expense of the other.

Successfully advancing clean energy innovation requires two categories of drivers. First are "demand-pull" drivers—for example, a price on carbon—which create favorable market conditions to sell low-carbon technologies to consumers. But a primed market alone is often insufficient to induce innovators to make risky investments in developing new technologies. So a second category, "technology-push" drivers, is needed to catalyze innovation through direct support for technology development and for demonstrations of new technologies at scale. Policy makers who only adopt a demand-pull strategy will not only fail to stimulate innovation but could actually discourage it if their policies end up deploying mature technology, enabling incumbent learning that raises the market entry barrier to emerging technologies. Moreover, such a policy approach can create powerful political constituencies in support of a particular clean energy technology and opposed to technological succession.

Finally, lock-in is most likely to occur in "legacy sectors," in which entrenched market structures and risk-averse actors discourage innovation. This is particularly true for energy. Indeed, lock-in is most common regarding fossil fuels, as behemoth incumbents such as major oil companies are well positioned to arrest a clean energy transition. But lock-in within clean energy is also driven by similar dynamics between incumbents and upstarts. For example, electric power utilities in the United States are very risk-averse, and as a major customer of renewable energy, they are likely to prefer mature technologies with extensive field experience. Another feature of legacy sectors is that disruptive products must be immediately competitive with market incumbents. So unlike the computing sector in the 1980s—when Apple sold the Mac Portable for over $13,000 (in 2016 dollars) but could attract customers because it was creating a new market—power from renewable energy must compete with power from fossil-fueled sources for market share. As a result, the playing field in legacy sectors such as energy is even further tilted against new technologies.



Cetacea

A submission to the 2016 Land Art Generator Initiative design competition for Santa Monica

Keegan Oneal, Sean Link, Caitlin Vanhauer, Colin Poranski (University of Oregon)

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The blue whale is a pelagic powerhouse. Consuming upwards of four tons of krill per day, the world's largest creatures are fueled by gargantuan quantities of its smallest. *Cetacea* reimagines the blue whale's strategy of capturing micro-sources of energy on an even larger scale.

Cetacea generates power by harvesting the renewable resources of Santa Monica Bay—wind, wave, and sun. Driven by the principle of "clean power for clean water," *Cetacea* reconciles water scarcity with pressing social and ecological concerns by supporting the existing water filtration facilities near the pier while providing carbon-neutral power to city residents.

Lock-in landscape

Nascent in some cases and entrenched in others, lock-in is already deterring innovation across a range of clean energy technology platforms.

Nuclear energy. Energy from nuclear fission is the clearest example of an energy platform mired in technological lock-in. Since the late 1950s, one type of nuclear reactor—the light-water reactor, which uses water to cool and moderate nuclear fission—has dominated global deployment of nuclear reactors. Although the economic benefits of scale were not central to the popularization of LWRs—the cost of building a reactor has actually increased over time—US public policy ensured that LWRs would dominate the world's nuclear fleet. But today, as nuclear's share of global electricity dwindles, the lack of diversity in nuclear technology is hampering efforts to deploy safer, cheaper, and more efficient nuclear reactors.

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The nuclear LWR got its big break from the US Navy. In the decade following World War II, then-Captain Hyman Rickover set out to develop a nuclear submarine that would have virtually unlimited range. At the time, the nuclear research community was far from consensus on the best type of nuclear reactor, and over 10 candidate designs were still considered viable. Rickover picked a short list of three reactor types, rapidly tested two of them, and decided to deploy LWRs across the submarine and aircraft carrier fleets. But even though a different reactor design may have been optimal for civilian use, Rickover chose to leverage naval expertise to make the first land-based nuclear reactor an LWR, giving the technology a decisive head start. From there, General Electric and Westinghouse built LWRs at home and abroad—leveraging federal assistance—to demonstrate US superiority in nuclear technology, halt proliferation of nuclear fuel (LWRs do not use weapons-grade fuel), and prevent the Soviet Union from winning over nonaligned countries with cheap nuclear power. Today, LWRs account for around 90% of all nuclear power capacity, and only Canada, Russia, and the United Kingdom have substantial power generation from alternative nuclear reactor designs, having resisted the US-led LWR campaign.

Within the United States, nuclear regulations passed in the 1970s cemented the dominance of LWR technology because regulations tailored to LWR reactors were ill-suited for alternative designs. These regulations allowed a firm to build duplicate plants and reuse major components without restarting the approval process each time. As a result, not only did all new domestic reactors use LWR technology, but each manufacturer's reactors began to homogeneously resemble a single, standard design, a de facto requirement to build reactors quickly and affordably. Since then, commissioning and constructing an alternative reactor design to the LWR has remained extremely difficult. And LWRs have faced their own steep obstacles, including construction delays, cost overruns, declining revenues in power markets, and political opposition from environmental and other constituencies. As a result, reactors are closing at a faster rate than new ones can be built.

This is unfortunate, because nuclear power is a more reliable power source than other zero-carbon sources, such as wind and solar, and because promising alternative designs have existed for decades. For example, post-LWR designs, called "Generation IV reactors," incorporate passive cooling systems that are much safer than the active cooling systems in existing LWRs, such as those that failed to prevent reactor meltdowns in Fukushima in Japan and on Three Mile Island in the United States. Moreover, alternative designs can be more efficient and enable modular construction approaches, reducing the cost of nuclear energy. Although these designs originated in the United States, China and Russia are investing heavily in commercializing Generation IV designs, with Canada, France, Korea, Japan, and the United Kingdom on their heels. If they succeed, US competitiveness in the nuclear industry will suffer, though global prospects for clean energy may improve. Still, after a half-century of technological lock-in, the odds are long for successful commercialization of new nuclear reactor technologies.

Biofuels. Similarly to nuclear energy, biofuels face hurdles to technological change because of public policies that have cultivated a dominant design and could tilt the playing field against emerging technologies vying for a share of a limited market. As a potential "drop-in" replacement for petroleum fuels, biofuels hold promise to reduce the carbon intensity of the transportation sector without requiring the major infrastructure changes that electric or hydrogen powered vehicles might require. However, the first generation of biofuels, which offer limited climate benefits and distort other sectors of the economy, continues to dominate the market to the exclusion of a preferable, second generation of biofuels.

The most common first-generation biofuel is ethanol, produced from corn in the United States or sugarcane in Brazil, which can then be blended into gasoline to fuel existing gasoline engines. Sugarcane ethanol has a considerably lower carbon footprint than US corn ethanol. But both corn and sugarcane ethanol displace agricultural activity, raise global food prices, and can deplete the supply of natural resources, such as water, for other uses. By contrast, second-generation ethanol—produced from the waste products or inedible parts of plants—could deliver greater greenhouse gas savings with fewer damaging side effects. Cellulosic ethanol is a promising but elusive class of second-generation biofuels. In 2015, the United States consumed just 2.2 million gallons of cellulosic ethanol, compared with 13.7 billion gallons of first-generation ethanol. However, prospects for cellulosic ethanol remain dim because of low investment in R&D and in the production facilities for advanced biofuel plants.

Over the past decade, US public policy has spurred a more than three-fold increase in domestic consumption of first-generation biofuels, making the United States the largest biofuel consumer in the world. And because US policy preferentially supported domestic production, the nation's corn ethanol producers reaped $20 billion in tax credits from the federal government from 2004 through 2010. In addition, Congress in 2005 established the Renewable Fuel Standard program mandating that from that year onward, refiners blend rising volumes of biofuels into conventional petroleum fuels each year through 2022. Although the policy set minimum quotas for both first- and second-generation biofuels, it has so far resulted almost exclusively in increasing volumes of corn ethanol in the US fuel supply.

The amount of ethanol in the US gasoline supply has now reached 10%, a threshold known as the "blend wall." Fuels that blend more than 10% ethanol may not be compatible with the older segment of the existing vehicle fleet. Therefore, the US biofuels market is now a cordoned-off market that pits first-generation against second-generation biofuels in a constrained market. Although the US Environmental Protection Agency has suggested that its future mandates might breach the blend wall, continued uncertainty over whether cellulosic ethanol will have to compete directly with corn ethanol may further chill the struggling cellulosic ethanol industry.

Still, there are some advantages from adoption of the first-generation fuel that could carry over to subsequent fuels. In the United States, widespread use of corn ethanol in the fuel mix has resulted in increased infrastructure for biofuels around the country (for example, storage tanks for ethanol at fueling stations). Moreover, newer cars are being equipped to tolerate more ethanol in the fuel mix than the 10% blend wall, and some vehicles, known as "flex-fuel" vehicles, can use up to 85% ethanol fuel.

Despite progress on the infrastructure front, prospects for decarbonizing the transportation sector with biofuels are dim because of the dominance of corn-based ethanol. The biofuels example demonstrates that even well-intentioned public policy, such as the federal Renewable Fuel Standard, can backfire by implicitly supporting a mature technology over an emerging competitor. And it is a cautionary tale for policy makers seeking to create political constituencies for clean energy through public deployment support. For although the architects of the fuel standard may have intended to foster both first- and second-generation biofuel industries, they unleashed a powerful lobby for first-generation biofuels alone, whose political sway is on display every four years in the Iowa presidential primary.

Solar energy. Although public policy has been the principal driver of entrenching incumbents in nuclear energy and biofuels, both economic and policy causes are needed to explain the technological stagnation of solar energy. Today, the first-generation solar photovoltaic (PV) material, silicon, accounts for over 90% of the solar PV market, even though the technology is more than 60 years old. Although silicon solar panels have recently plummeted in cost, enabling rapid market expansion, it is unclear if silicon solar can improve enough on cost and performance to materially displace fossil fuel-based power from coal and natural gas.

Silicon solar exemplifies the economic advantages of incumbency: as its production has grown, its costs have predictably fallen. Silicon solar quickly became the dominant design in the second half of the twentieth century because the solar industry was able to adapt the equipment and manufacturing processes used in the fast-growing semiconductor industry to instead produce silicon solar panels. Then, from 1978 to 2015, the real cost of a solar panel declined from $80 per watt to below $0.50 per watt, or around a 24% drop in cost for every doubling of cumulative production. Much of this decline was due to public and private R&D. But as silicon technology has plateaued in recent years, the cost improvements have been dominated by "learning-by-doing," as producers incrementally improved the manufacturing processes and performance of silicon solar panels. In addition, as the adoption of solar in a particular market has increased, all of the "balance-of-system" costs (for example, installation, equipment, labor) that exclude the physical solar panel have also decreased as companies get better at deploying solar. For example, over the past five years alone, the balance-of-system cost for installing solar in the United States has halved and is projected to decrease 85% over the next 15 years.

In addition to the economic advantages conferred by learning, silicon solar has benefited from public policies focused heavily on the deployment of renewable energy. Through 2015, Germany alone had spent over $66 billion to support the deployment of solar power. And whereas Germany is presently scaling back support for solar, other countries, including the United States, China, and India, are aggressively extending policy support for solar. For example, in 2015 the United States extended its 30% solar tax credit through 2021, at a projected cost of nearly $10 billion. None of these policies distinguishes between mature and emerging technologies; as a result, subsidies have indirectly supported the deployment of silicon solar.

More directly, the Chinese government lavished financial support for silicon solar produced by local industry. From 2010 to 2011 alone, the China Development Bank extended $47 billion in lines of credit to major Chinese manufacturers, spurring them to scale up rapidly, even as profit margins collapsed from a supply glut. The flood of cheap Chinese silicon solar panels washed away innovative start-up companies in the United States, many from Silicon Valley. In 2012, the United States began levying tariffs on Chinese panels to countervail below-cost "dumping" of silicon solar panels. But by then the damage to US solar start-ups had been done, and none would go on to achieve significant market share. Recently, the rate of new company formation in solar has plummeted as investor interest in new solar technologies has waned.

Still, given the rapid growth of the solar market and the continued cost reductions of silicon solar, it might appear that no alternative to silicon is really necessary to meet global decarbonization goals. Such optimism is misplaced. Materially displacing fossil-fuel energy from natural gas and coal will require many terawatts of installed solar capacity—over an order of magnitude greater than existing installed capacity. At such a high penetration of solar, the cost target for solar to compete with fossil fuels will likely drop considerably; solar becomes far less valuable to the grid as more of it is installed, owing to the intermittency of sunlight. Energy storage and more responsive electricity demand could shore up some, but not all, of solar's declining value. Indeed, for solar to provide 30% of global electricity production by 2050, Shayle Kann and I have estimated in *Nature Energy* that solar will have to cost less than $0.25 per watt, which is over four times lower than current costs. Extrapolating historical learning effects, that figure is simply out of range for silicon solar. And if silicon solar hits a penetration ceiling decades from now and a clear investment case emerges for a superior technology, it may be too late to keep global decarbonization on track.

Given that exciting discoveries continue to emerge from research laboratories, it is premature to conclude that solar PV as a platform is destined for technological lock-in. Devices made from alternative materials to silicon that are abundant, cheap to produce, and highly customizable are close to matching the performance of silicon solar devices. (One particularly promising alternative is called perovskite, a wide-ranging class of materials in which organic molecules made mostly of carbon and hydrogen bind with a metal, such as lead, and a halogen, such as chlorine, in a three-dimensional crystal lattice.) Soon, such alternatives might surpass silicon. However, silicon solar appears to function much more as a barrier than a bridge to the adoption of more advanced technologies. Ever more finely tuned processes to manufacture silicon cells and panels are not transferrable to the radically different (and, theoretically, much simpler) processes to print next-generation solar coatings. Extensive industry experience installing silicon solar panels is mostly irrelevant for future construction projects that may use building-integrated solar materials. And novel financing arrangements—for example, to securitize solar project debt—are emerging because a wealth of operating data from actual silicon panels has allayed investor fears about performance risk, but investors may well be wary of using the same financial instruments with less proven technologies. So even if some industry advances do apply to multiple solar technologies, the rise of silicon solar has mostly reinforced its position as the platform's dominant technology.

Energy storage. Lithium-ion batteries could follow in silicon solar's footsteps, amassing the learning benefits of incumbency and posing a barrier to market entry for other energy storage technologies. At present, lithium-ion technology dominates the still-nascent energy storage market, a sector that could be crucial to large-scale decarbonization by enabling electric vehicles and electric grids powered by intermittent renewable energy. But lithium-ion appears to be a suboptimal technology for either application, and superior alternatives may not gain market traction if energy storage succumbs to technological lock-in.

The lithium-ion battery got its start in consumer electronics; Sony commercialized it in 1991 to power camcorders. Since then, laptop and mobile phone applications have driven a dramatic scale-up of lithium-ion production capacity, mostly in Asia. These producers could then build on existing scale to be first-movers into new markets. First, over the past decade they sold batteries to major car companies, such as General Motors and Tesla, which released hybrid and fully electric vehicles powered by lithium-ion batteries. And most recently, utilities and consumers have begun installing lithium-ion batteries to stabilize the power grid and lower electric bills.

In all of these markets, producers of lithium-ion batteries are virtually unchallenged and are amassing the economic benefits of scale. Just as the cost of silicon solar panels dropped, the cost of lithium-ion batteries has fallen by 22% for every doubling of cumulative production since 2010. And in 2016, Tesla opened the first phase of its "Gigafactory" that by 2020 will produce more lithium-ion batteries than the entire world's production in 2013. Chinese and European car manufacturers are looking to follow suit, suggesting that costs will continue to fall with lithium-ion's scale-up.

But there are limits to how far a lithium-ion powered car can be driven or how much intermittent renewable energy on the grid lithium-ion batteries can buffer. An affordable car with a 500-kilometer range will require batteries that cost $100 per kilowatt-hour and store 350 watt-hours per kilogram—neither of which is realistic for lithium-ion. In addition, energy storage solutions need to tolerate between three and 10 times more lifetime cycles than lithium-ion batteries to cheaply and reliably stabilize the power grid.

Alternative battery chemistries—such as lithium-air, lithium-sulfur, or magnesium-ion batteries—could theoretically deliver the required performance. But they will need R&D support and private investment dollars to achieve scale. In the meantime, deployment-focused public policy, especially in the United States, might implicitly support mature solutions and further increase their cost advantage over would-be competitors. And with each passing year, the risk of technological lock-in to lithium-ion batteries grows.

Escaping lock-in

Even in energy, the archetypal legacy sector, technology lock-in does not have to be inevitable. In fact, two technology platforms—efficient lighting and wind energy—are on pace for continued technological improvement. These examples offer distinct but related lessons for how to escape technological lock-in.

Efficient lighting. In the early 2000s, US public policy favored compact fluorescent lightbulbs (CFLs) as the preferred alternative to conventional incandescent bulbs. CFLs were five times more energy-efficient and lasted 10 times as long, providing compelling environmental and cost benefits. As utilities and the federal government aggressively promoted them, CFLs reached 20% market share by 2007. But, unexpectedly, CFL market share has since tapered down to 15%, and a rival efficient lighting technology, the light-emitting diode (LED) bulb, has risen to the same market share. LEDs are a superior technology to CFLs. They are more dimmable, more efficient, over three times more long-lasting, and more versatile in their range of colors and sizes. So it is a sign of a functional technology

ESTHER

A submission to the 2016 Land Art Generator Initiative design competition for Santa Monica

Peter Coombe, Jennifer Sage, Eunkyoung Kim, Charlene Chai, Kaitlin Faherty (Sage and Coombe Architects)

New York, New York

ESTHER captures the ephemerality of motion through water and air, harnessing these elements to generate purified water and clean energy. The design is conceived as two parts: an underwater point absorber buoy that harvests wave energy, and a piezoelectric torque generator "mast" that collects wind energy as it sways above water.

This two-part design takes inspiration from synchronized swimming, as epitomized by the classic aqua-musicals of Esther Williams from the golden years of Hollywood in the 1940s and 1950s.

transition that LEDs will continue to gain at the expense of both incandescents and CFLs; General Electric projects 50% LED penetration by 2020 and 80% by 2030.

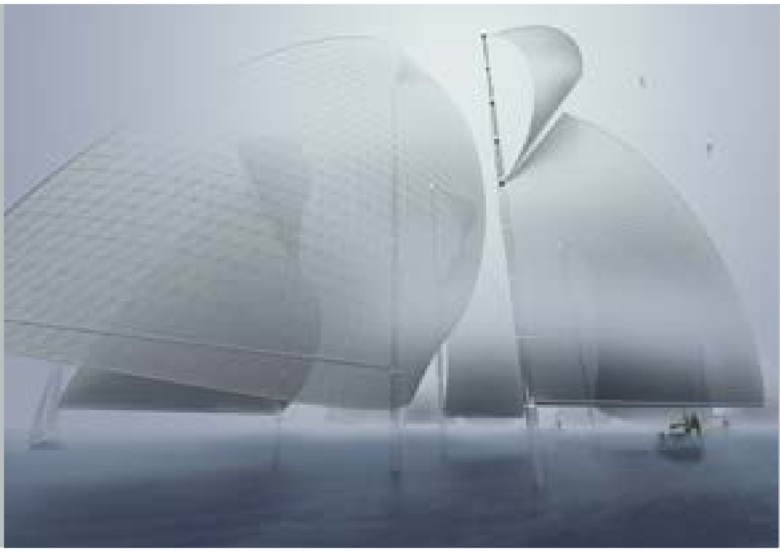
The ongoing success of this technology transition proves that lock-in to a first generation clean technology is not inevitable, even with the deck stacked against a second-generation successor. As in other platforms, the first-generation technology—CFLs—enjoyed the economic advantages of scale, halving in cost for every doubling of production from 1998 to 2007. And through technology-neutral deployment regulations, government policy implicitly favored CFLs that already had achieved scale. For example, in 2007, Congress passed legislation requiring lightbulbs to be 60% more efficient by 2020—a threshold that both CFLs and LEDs met—rather than rewarding LEDs for being even more efficient than CFLs.

Despite these barriers, LEDs broke into the lighting market through decades of technology development and commercialization in niche, or "stepping-stone," markets, demonstrating a potential path forward for advanced technologies in locked-in platforms. From 1968 to 1990, LED producers built up experience with the technology by meeting demand for specialized lighting applications, such as electronic displays and indicator lamps. From there, they branched out to larger-scale markets from 1991 onward, taking over traffic signals and vehicle lights. Over a half-century of scaling up, LEDs fell in cost by a factor of 10 every decade, a regularity known as "Haitz's Law" (a cousin of "Moore's Law" for integrated circuits). LED performance also improved dramatically as companies such as Philips invested in R&D. And over the 2000s, US government support for LED R&D grew to over $100 million annually, some of which the Department of Energy (DOE) directed toward commercialization, including testing new technologies in real-world conditions through industry partnerships with national laboratories.

Finally, by 2013, producers could manufacture and sell LEDs that emitted warm, white light for $10 a bulb, cost-competitive on a lifetime basis not only with CFLs but with traditional incandescents as well. They will get only cheaper and perform better: by 2020, an LED bulb will cost $5 and produce twice as much light per watt. But it is crucial to remember that LEDs did not appear on the global lighting stage out of nowhere; decades of development and scale-up through stepping-stone markets enabled LEDs to vanquish lock-in.

This lesson may be most applicable to energy storage, a technology platform with an array of applications that rivals the diversity of LED uses. Indeed, lithium-ion technology benefited from a stepping-stone market, gaining scale and experience in consumer electronics before firms applied the technology to electric vehicles and grid-scale storage. If alternatives can also gain scale through a stepping-stone market—for example, by providing back-up power to military bases—then they may be able to compete with lithium-ion on a more level playing field.

Wind energy. As in the efficient lighting platform, wind energy has exhibited consistent technological improvement. But unlike the transition from first-generation CFLs to second-generation LEDs, performance gains in wind have not required paradigm shifts in technology. Instead, they have resulted from consistent



Regatta H_2O: Familiar Form, Chameleon Infrastucture

A submission to the 2016 Land Art Generator Initiative design competition for Santa Monica

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Tokyo, Japan

Regatta H_2O repurposes this familiar maritime form as infrastructure, which harvests fog to create fresh water and harnesses the wind in order to power its operations. The sails of *Regatta H_2O* are fog-harvesting meshes. Collection troughs are designed as veins within the sail surface, transporting harvested moisture to the mast where it can be piped to storage vessels at the Santa Monica Pier. When the moisture content of the air falls below a certain threshold, the sails are retracted to reveal the horizon line of the Pacific Ocean.

and incremental technological progress.

During the 1970s, which saw the first major wind installations, firms tested various designs and quickly settled on the three-blade, horizontal-axis wind turbine, which remains the dominant design today. So in a strict sense, wind energy has experienced technological lock-in; but there are no compelling alternatives being locked out. Compared with the vertical axis wind turbine, the horizontal-axis version is cheaper and more efficient, and three-blade rotors turn out to be more balanced and efficient than two- or one-blade configurations.

As a result of quick industry alignment around the optimal configuration, wind energy was set up for continued incremental progress. For example, from 1999 to 2013, an average wind turbine's output increased by roughly 260% as firms developed taller towers and longer blades, blade pitch control and variable speed, advanced materials and coatings, sophisticated control systems, and a variety of other electro-mechanical improvements. These upgrades were incremental; having fixed the overall system configuration, firms could then independently develop, test, and commercialize improvements to each subsystem. Looking ahead, the wind sector may yet confront a technology transition as firms invest heavily in offshore wind technology. But this paradigm shift might sidestep lock-in through a series of incremental improvements, including making even larger wind turbines than onshore models and adapting the oil and gas industry's expertise in floating platform design.

Because incremental innovation works so well for improving the performance and reducing the cost of wind energy, wind may respond differently to technology-push and demand-pull public policies than other technology platforms. For example, a 2013 study from Carnegie Mellon suggests that state-level policies mandating that utilities procure a certain amount of renewable energy actually induced more wind energy patents than public R&D funding did. In other platforms, such as solar power, such deployment-focused policies are insufficient to convince private investors to fund costly R&D and production of alternative materials that are fundamentally different than first-generation solar panels. But in wind energy, firms are willing to make smaller investments in incremental improvements to existing wind turbines that can quickly pay off.

This difference suggests that the wind energy platform is an imperfect guide for other clean energy technology platforms mired in technological lock-in. But the example of wind energy still teaches the important lessons that incremental innovation is much easier to accomplish than an overhaul of the dominant design and that a series of evolutionary steps can ultimately yield a revolutionary product. Some observers have proposed similar paths to enable other technology platforms to escape lock-in. For example, firms miniaturizing nuclear LWRs hope to alter US nuclear regulations to more flexibly assess small modular reactors (SMRs). Although SMRs are evolutionary descendants of the traditional LWRs, a more flexible regulatory regime might reduce the barriers to development of advanced Generation IV reactors. As an incremental intermediary, SMRs could bridge the gap between the locked-in nuclear industry today and improved technologies in the future.

Similarly, the solar industry could transition to more advanced materials through an incremental route. For example, some firms developing solar perovskite coatings plan to layer the coatings on top of existing silicon solar cells to boost the performance of existing solar panels. This way, an upstart technology does not require massive scale to compete with giant industry incumbents; the second-generation technology would piggyback on the success of the first-generation. And once solar perovskites achieve production scale, firms might try to make solar perovskite coatings without the underlying silicon panel, unlocking brand new markets and capabilities for solar.

Marrying innovation and deployment policy

As these diverse examples demonstrate, there is neither a single route to technological lock-in nor any ironclad prescription to avoid it. Nevertheless, public policy should strive to minimize the risk of first-generation technologies stifling competition and maximize prospects for superior successor technologies to enter the market.

Policy makers looking to advance clean energy should begin by following the example of newly minted doctors who swear to "do no harm." As experience with other energy technologies has shown, well-intentioned public policies that aim to deploy clean energy can backfire by stunting innovation. This can happen when a policy creates a ring-fenced market, effectively pitting current-generation and next-generation clean energy technology against each other in an unfair fight. The Renewable Fuels Standard has created such a situation, now that first-generation corn ethanol accounts for nearly the entire volume of fuel that can be blended into gasoline and still be widely usable by the vehicle fleet. Moving forward, advanced biofuel quotas should increase at the expense of corn ethanol quotas so that the latter does not crowd out next-generation technology with clear public benefits. But this will be politically challenging, because by expanding the corn ethanol industry, the fuel standard has unleashed a political constituency opposed to technological succession.

Moreover, demand-pull policies alone can be insufficient to induce innovation; for example, even with rising advanced biofuel quotas over the past decade, production has remained insignificant. In addition, technology-push policies are a necessary complement. Thus, the Obama administration was right to propose doubling investment in energy R&D to $12.8 billion from $6.4 billion by 2021. Although strong institutions such as the National Science Foundation (NSF) and DOE national laboratories have historically funded and performed energy R&D, these efforts should be modernized as funding expands. Newer institutions such as the DOE's Advanced Research Projects Agency, which can flexibly set funding priorities for breakthrough technologies, should grow over time.

Still, the federal government is much better at funding R&D than it is at supporting first-of-a-kind demonstration projects or production scale-up, leaving innovative technologies to languish in a "valley of death" without public or private investment. Part of this failure is due to a mismatch in institutions—whereas DOE and NSF reliably underwrite R&D, DOE's investments in demonstration projects are erratic and politically sensitive. New institutions at the federal or regional levels, or both, are needed to fund demonstration projects and de-risk emerging technologies to embolden private investment in them. In the long term, the United States should redesign its legacy institutional architecture, much as the United Kingdom developed a new set of institutions from scratch to reduce emissions and advance end-to-end clean energy innovation.

Finally, taking inspiration from the example of LEDs crossing the valley of death via stepping-stone markets, policy makers should use public procurement to provide early markets for emerging technologies that otherwise are unlikely to attract private investment to take on established incumbents. This strategy has been wildly successful in other fields. For example, the military's semiconductor procurement in the 1960s directly led to the development of the integrated circuit, which revolutionized computing. In the global health sector, governments around the world pooled $1.5 billion in 2007 as an "advance market commitment" for a pneumonia vaccine, succeeding in pulling new drugs onto the market that would otherwise have been unprofitable ventures. Yet another model is the National Aeronautics and Space Administration's payments to firms such as SpaceX to accomplish milestones toward the ultimate goal of transporting cargo and crew to space and back. Similar approaches could elicit private investment in clean energy technologies that could scale up in publicly guaranteed stepping-stone markets.

In particular, the military could make a compelling case that revolutionizing locked-in technology platforms would advance its objectives. Small modular nuclear reactors could power military bases at home. Lightweight but high-performance solar panels and batteries could offer operational flexibility in the field. And biofuels capable of displacing oil at scale could not only fuel the military's operations but also reduce the risk of an oil-supply disruption that the military aims to prevent. But for this approach to successfully induce new products, military procurement would have to be carefully coordinated with public funding for earlier stages of technology R&D and demonstration.

In shepherding emerging clean energy technologies from lab discoveries, through the valley of death, and ultimately into commercial markets, policy makers must delicately balance competing goals. On one hand, investors and entrepreneurs need assurances that public policy will support a market for their products down the road. But on the other hand, once a technology achieves commercial maturity, policies to support their deployment need to leave room for the next generation of technology to emerge and compete. Thus, policy makers should enact intelligent deployment policies that dovetail with support for innovation, such as auctions that put a price on greenhouse gas emissions and raise revenue for technology-push policies.

This approach could accelerate financial and business model innovation driven by deployment of existing technology, which, in turn, could make it easier for next-generation technologies to succeed. That must be the guiding logic behind clean energy policy—to transform lock-in barriers into bridges for technological succession.

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