Energy System Transformation for a 1.5°C Future

Climate Tech's Perfect Storm

Harnessing Technology and History to Keep Warming below 1.5°C

By: Rudy Kahsar
Contributor: Charlie Bloch

STRATEGIC ENGAGEMENT AND ANALYSIS GROUP

Businesses, governments, and other institutions are facing increasing pressure to mitigate the worst impacts of climate change by dramatically reducing emissions in line with the Paris Agreement. However, the strategists, analysts, and decision makers whose actions will shape the necessary market and policy transformations may be challenged to see past legacy modeling approaches and assumptions. These approaches and assumptions capture neither the massive economic opportunities for early movers nor the compounding risks of being left behind.

To strengthen this interface, RMI is releasing a series of insight briefs to help demystify the available tools for 1.5°C alignment, identify critical gaps that require complementary approaches, and highlight emerging opportunities to reinvent the future. **These insights are bound by our assessment that a rapid transition to a low-carbon energy system is not only achievable, but also a source of growth, prosperity, and benefit for all.**

Technological innovation is one of several market catalysts that are accelerating the clean-energy transition. The rapid cost and performance improvements of wind, solar, and batteries alongside advancements in areas such as artificial intelligence, automation, Internet of Things (IoT), and manufacturing are leading to new, disruptive technology combinations. These innovations are opening new markets for clean-energy technologies, driving further cost declines, and providing additional support for a low-carbon future.

As a result, we are at a critical moment in history when the global energy system and economy are poised to change in cascading ways. Policymakers and businesses will prepare for and contribute to such a transition much differently than in business-as-usual strategies. Rather than simply keeping up with tech advances, strategies for an era of disruption require a scenario approach, as whole ecosystems of technologies may be transformed.

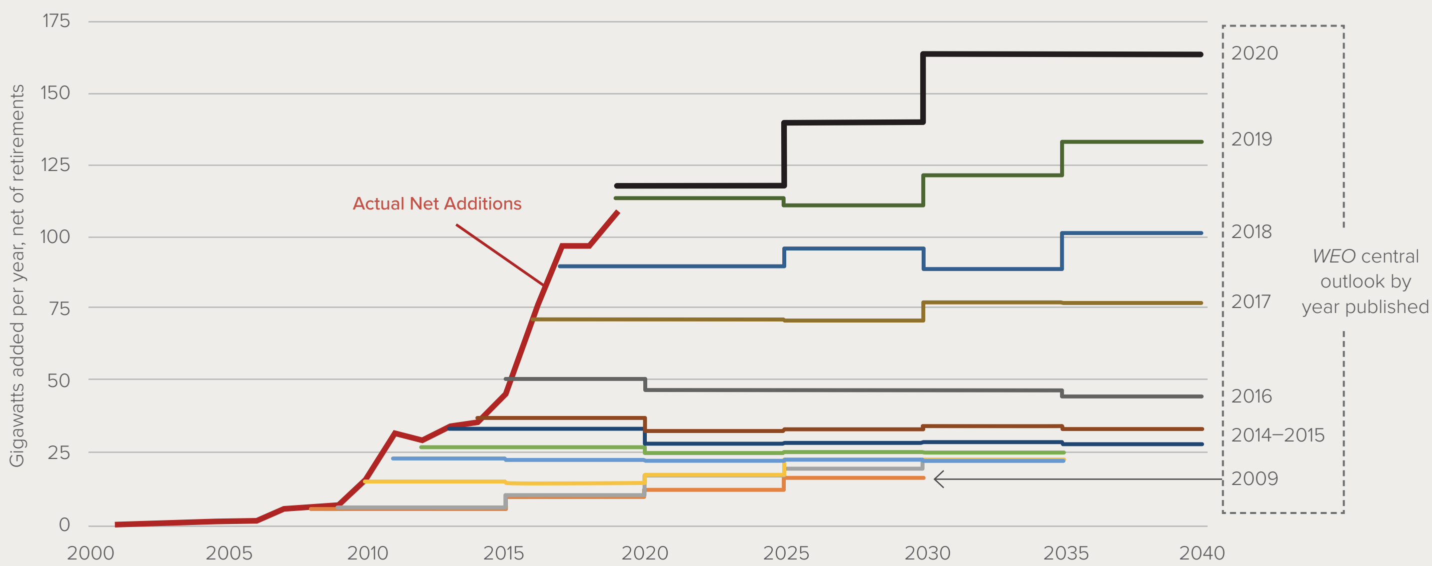
Technology Innovation Is Essential for 1.5°C Targets

Rapid development, scaling, and adoption of new technologies are critical to limiting global warming to 1.5°C. According to the International Energy Agency (IEA) report *Energy Technology Perspectives 2020*, or *ETP*, around 50% of the emissions reductions needed to reach net zero by 2050 require technologies that are not yet commercial today.[1] For heavy industry and long-distance transport, the IEA estimates are closer to 75%. But these daunting statistics may overstate the challenge. The *ETP* scenarios' assumptions are "broadly consistent" with the IEA's flagship report, the *World Energy Outlook (WEO)*, which has famously underestimated the growth of new technologies.[2]

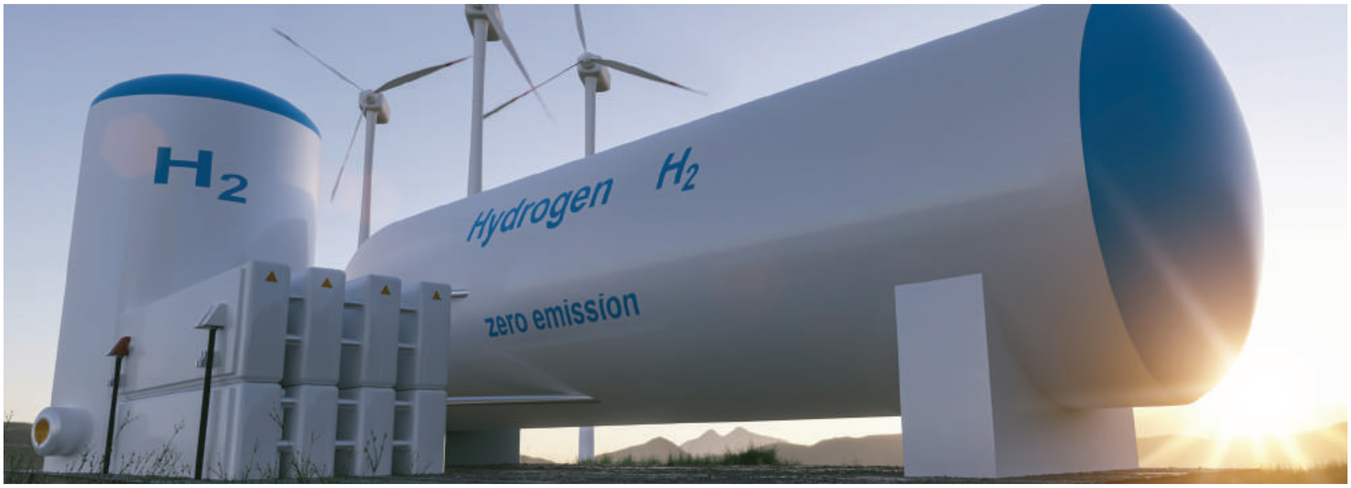
For example, the IEA's *WEO* has consistently and significantly underestimated the deployment of solar PV (Exhibit 1) since at least 1994.[3] According to the Energy Watch Group, a Berlin-based think tank, a key reason for this underestimation is that the IEA has assumed that these technologies remain in an early, linear growth phase as opposed to the exponential portion of their respective S-curves.[4] Furthermore, the slope of the exponential phase has increased dramatically in the past 20 years, particularly for standardizable and mass-produced products such as cell phones, computers, lithium-ion batteries, and solar PV cells.[5]

EXHIBIT 1

Net solar capacity projected additions from the IEA's *World Energy Outlook*



Source: RMI, IEA



The *WEO* isn't the only model to underestimate the deployment of renewable energy. New research shows that IPCC baseline scenarios have systematically overprojected carbon dioxide emissions, the use of coal power, and economic growth.[6] Most of the major oil companies' energy forecasts also understate the uptake of renewable energy. Even analyses from organizations such as BloombergNEF, which generally project faster rates of adoption, have at times underestimated the deployment of new technology. Many of these models, like the *WEO*, project linear extrapolations of the past—a pragmatic hypothesis, but one that does not match reality. Disruptive technologies follow nonlinear diffusion curves.[7]

How Disruptive Technologies Take Over

For the most part, technological disruptions don't come from a sudden breakthrough but from the accumulation of incremental improvements. In some instances, parallel improvements in multiple aspects of a technology cause periodic leaps in performance or cost reduction. Over time, however, technologies' costs tend to decrease at a constant rate for every doubling in cumulative production, in a relationship known as learning effects.[8]

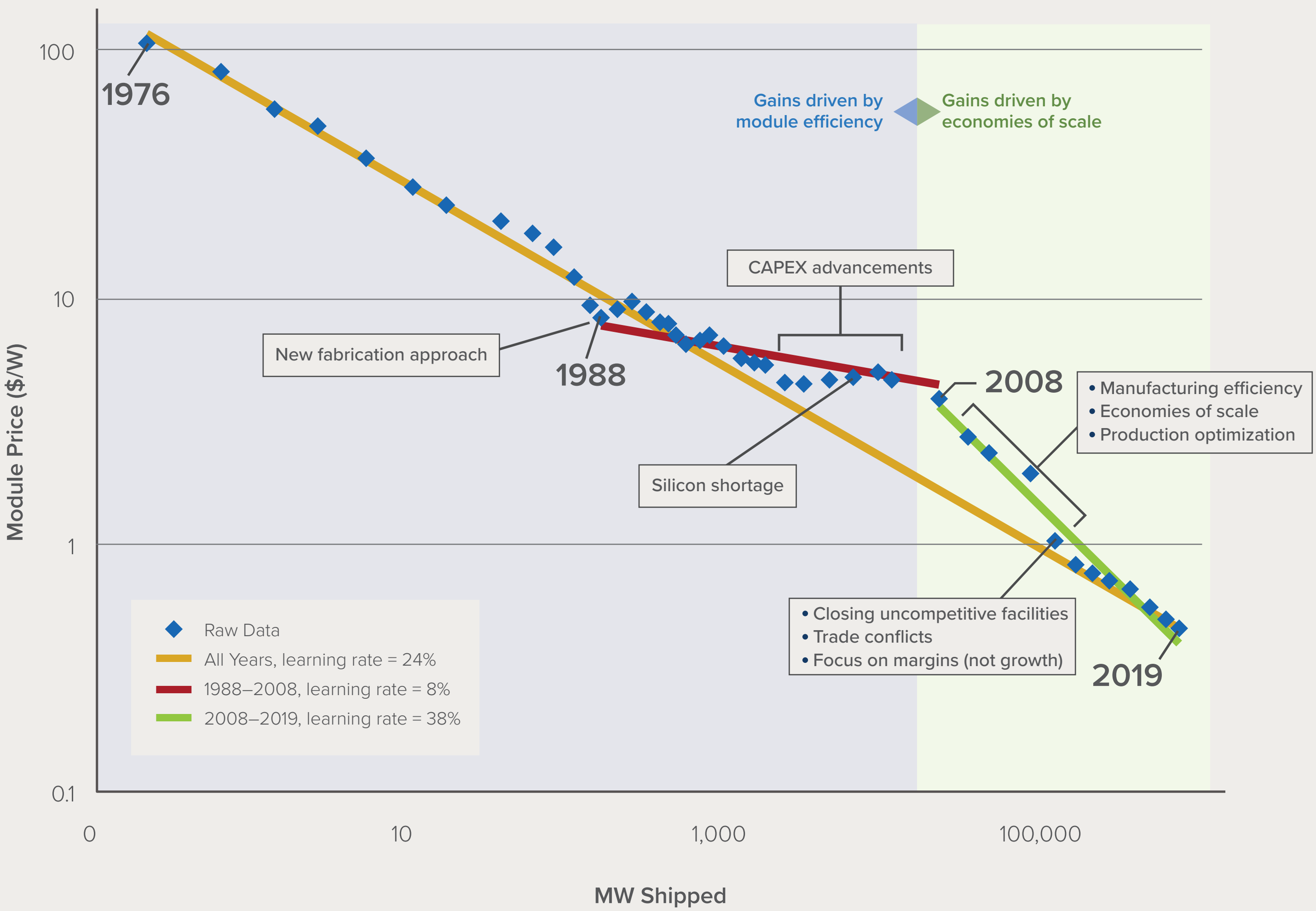
While learning effects may seem obvious in retrospect, they often feel like an oversimplification in real time, making incumbents skeptical of their utility. But learning effects need not be so mysterious. Underneath the high-level trend is a combination or succession of different factors that reproducibly drive down cost, including efficiency, new materials, better manufacturing processes, supply chain optimization, and scale effects.

The learning curve for solar PV (Exhibit 2) helps to illustrate this dynamic.[9] The yellow line, which shows the overall learning rate for PV from 1975 to 2019, illustrates a clear long-term learning trend of 24%. But this long view fails to explain the nuances of PV's cost-improvement trajectory from year to year.

A 2018 paper from Jessika Trancik of the Massachusetts Institute of Technology and her coauthors broke down solar PV's cost declines into two major phases: *an early period where advancement was defined by publicly funded research and development (R&D) and a second phase where improvements were driven by market-stimulating policies.*[10] A variety of additional subfactors at an even more granular level further contribute to the overall slope of the learning curve.

EXHIBIT 2

Learning curve for silicon solar PV, broken out by periods and drivers.



Source: Our World in Data,[11] RMI

Other emissions-reducing technologies show similar phases of learning characterized by R&D gains, scaling, and mass production. The lesson from solar PV is that clean technology can follow a scalable growth trajectory, and that we can travel it again with the right encouragement at the right times. In the 2020s, a variety of forces are aligning that will accelerate new advances in cleantech.

Forces Are Aligning for Exponential Change

Three critical factors suggest that the current resurgence in clean-energy and climate-tech venture capital is likely to lead to greater success than the "cleantech 1.0" boom-and-bust investment cycle in the late 2000s.[12] Those factors are: convergence of technology, sharing of innovation, and a policy landscape that is increasingly urgent and authentic.

The Convergence of Tech and Climate Mitigation

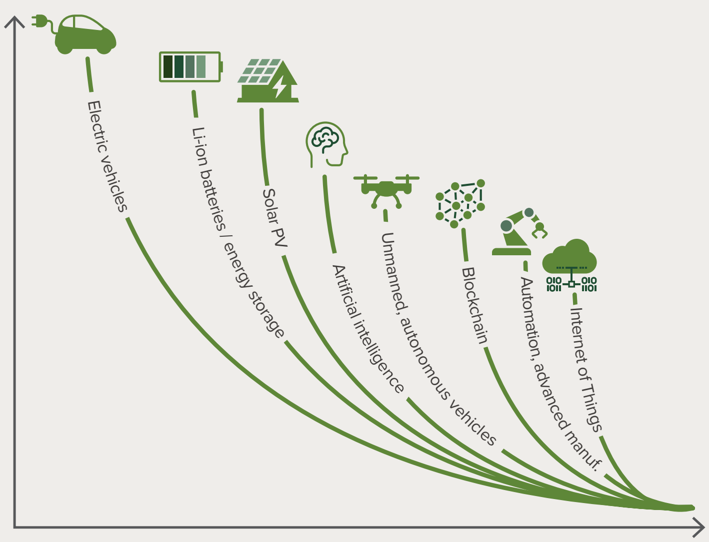
In the decade or so since the Great Recession and the cleantech 1.0 wave, technologies such as wind and solar PV have been joined by a whole new ecosystem of technologies, including advanced control systems as well as low-cost inverters, peripherals, and batteries. In addition, the continued proliferation of IoT hardware and artificial intelligence advancements continue to create rapid paths to solution development and improvement. The opportunities that lie at the intersections of these disparate technologies will trigger breakthrough innovation.

Entrepreneur and innovation expert Tony Seba describes this convergence effect by highlighting that the smartphone became possible precisely in 2007 (not 2006 or 2008). In 2007, the simultaneous advancement of each of a variety of individual component technologies created the technical possibility of a $600 integrated device.[13]

In the 2020s a variety of newly powerful and inexpensive technologies will similarly drive convergence in the climate-tech space (Exhibit 3). From 2009 to 2020 the levelized cost of solar PV decreased by 90% and wind by 71%.[14] The cost of grid-scale battery storage fell 76% from 2012 to 2019.[15] According to Goldman Sachs, the cost of tiny sensors, including cameras, gyroscopes, and accelerometers, dropped by more than half between 2004 and 2014. In 2020 the total number of IoT devices (11.7 billion) exceeded the number of non-IoT devices (9.9 billion) worldwide for the first time. Analysts expect that by 2025 there will be 30 billion IoT devices connected to the Internet.[16]

EXHIBIT 3

Simultaneous cost reductions and performance improvements across diverse industries create unprecedented possibilities for emissions-reducing technologies



Converging Technologies	Innovation	Incumbent
	Shared, connected, autonomous, electric mobility	Single-occupant internal combustion engine vehicles
	Transparent, streamlined, verifiable supply chains and logistics	Opaque, less efficient, nondigitized supply chains, with unclear carbon accounting
	Efficient, smart, electric buildings	Less efficient buildings with unoptimized systems and greater fossil fuel dependence

Source: Tony Seba, RMI

Other advances in artificial intelligence, drones, autonomous transportation, robotics, and automation have been equally dramatic. The confluence of these technologies will open up new business opportunities. For example, IoT, advanced controls, and low-cost batteries are enabling companies such as Sunrun to aggregate customer-sited batteries for demand response and load shifting in partnership with Open Access Technology International.[17]

Mindful of the fact that disruptors have often overtaken incumbents, today's largest corporations are investing significantly and strategically in data, automation, and the Internet of Things. According to McKinsey, "reinvented incumbents"—those companies embracing disruptive technologies—are investing three times more in disruptive technologies than traditional incumbents.[18] Corporate venture capital (CVC) has also grown rapidly since 2013, with 429 active CVCs in the fourth quarter of 2018, up 35% on the year and including ventures from Maersk, Porsche, Salesforce, Mitsubishi, Shell, Google's GV, and Microsoft's M12.[19]

Cross-Sector Synergies: Sharing Technology

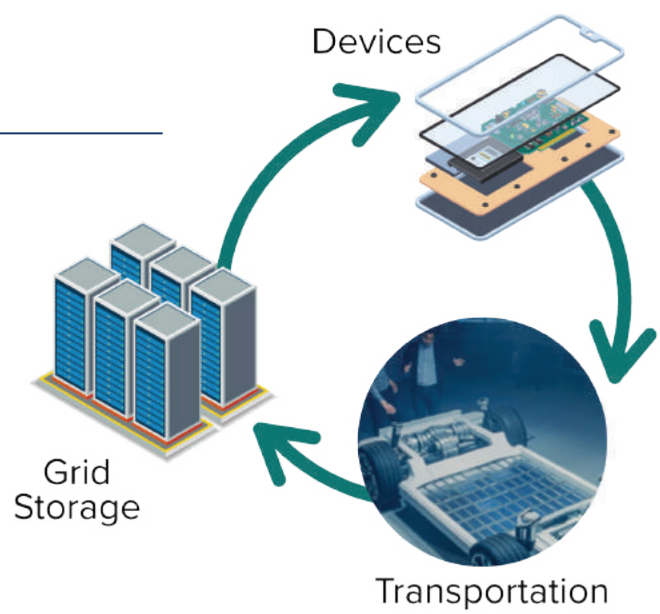
Increasingly, the crossover of technologies into new applications creates entirely new markets and demand streams that can further accelerate performance and cost improvements. When General Motors' EV1 emerged in 1996, it marked not only the launch of a new technology (the world's first mass-produced electric vehicle), but also a nascent demand for battery technology. At that point, batteries were still too costly and lacked the energy density required for mass adoption. As demand for cell phones and other consumer electronics skyrocketed, however, the cost dropped and performance surged as lithium-ion battery technology accelerated along its learning curve.

Today, Li-ion batteries power not only a rising number of personal devices, but also a new era of electric mobility and stationary electricity storage (Exhibit 4). As cost and performance trends continue in the 2020s, they may soon open the possibility of additional crossover applications in vehicle fast charging, vehicle-to-grid charging, and long-duration electricity storage. Technology crossover within innovation ecosystems can accelerate disruption by providing a wider range of inputs, sourcing, and demand as well as shared personnel, manufacturing infrastructure, and risk.

EXHIBIT 4

Li-ion batteries are a clear example of how a technology's use across multiple applications can accelerate learning, cost improvements, and deployment through shared knowledge, supply chains, and other spillover effects

Source: RMI



Another promising ecosystem with cross-sector potential is green hydrogen (hydrogen produced solely from zero-emissions electricity).[20] Green hydrogen could help solve various problems within the energy transition, particularly in decarbonizing the industrial sector's production of cement, steel, and petrochemicals as well as shipping and aviation.[21] It could also help address the need for long-duration energy storage.[22]

Development of a hydrogen ecosystem is already under way in Europe. During the European Hydrogen Week in November 2020, 62 signatories to a coalition statement pledged to deliver between 5,000 and 10,000 hydrogen-powered trucks by 2025 and a minimum of 100 hydrogen refueling stations.[23] The signatories included OEMs as well as fuel-cell and hydrogen technology suppliers representing the entire supply chain. The coalition foresees that up to 100,000 hydrogen-powered trucks and 1,500 stations could be deployed by 2030, along with 40 GW of electrolyzers.[24] In the manufacturing space, Siemens, Equinor, and Mitsubishi Power are all working on developing hydrogen-combustion systems, and Siemens Gamesa and Siemens Energy recently announced a €120 million ($145 million) demonstration of an integrated offshore-wind solution for producing hydrogen.[25]

Urgent Climate Policy: The Will to Change

Unlike its forerunner, the current clean-energy and climate-tech investment boom will be defined by urgent and authentic political willpower. Fearing the downside risks of a changing climate, governments are already taking serious action, including clean-energy mandates and net-zero commitments from countries representing about 50% of global GDP and current carbon emissions.[26] The United States, which just rejoined the Paris Agreement, represents an additional 15%–16% of each of those categories.[27]

In search of upside potential, companies and nations are investing in the new wave of technology. The EU has committed to a variety of policies for green hydrogen. India is investing billions to lure EV battery makers.[28] In the United States, the Biden administration plans to spend $2 trillion on the clean-energy economy over the next four years.[29] Bill Gates has proposed the creation of the National Institutes of Energy Innovation, with separate institutes that focus on areas such as transportation, energy storage, renewables, and CCS.[30] The policy and spending commitments now being made by governments around the world coincide with the rapid maturation of the climate-tech space, benefiting from the effects of convergence, synergy, and sharing in technology-innovation ecosystems. In the current environment, changes across multiple levels of technology, the economy, and society will begin to cascade to drive more rapid and far-reaching shifts than have characterized the global economy in recent decades. While infrequent, these periods of rapid and deep economic transformation—such as the Industrial Revolution—are a consistent feature in the long sweep of history.[31]

Researchers have demonstrated that technological change at the system level does not come as steady, incremental, linear progress. Instead change occurs in cascades, like avalanches on the sides of a steadily growing sandpile. Many of these cascades are small, but occasionally a massive cascade is triggered when many parts of the systems begin to interact and change all at once.[32] Understandably, conventional energy-economic models are hard-pressed to capture the systems dynamics for changes that occur very infrequently, perhaps less than once a century. Yet this is exactly the nature of the transformation that we must trigger to limit warming to 1.5°C.

How to Reinforce Innovation Ecosystems

In times of economic transformation, the interactions of market catalysts such as learning effects can dramatically accelerate the competitiveness of new technologies and business models. In many cases, the incumbents behind legacy solutions will spend more time and effort defending their shrinking market share and profits than investing in the disruptive technology. Similarly, governments that fail to anticipate the speed of disruption may have to scramble to encourage a domestic industry and avoid conceding a new market to foreign suppliers.

Businesses and policymakers can employ various approaches to accelerate the inception, development, and deployment of disruptive technology.

Approaches for Policymakers

Consider more rapid cost-decline trajectories than most scenarios suggest: First and foremost, policymakers should remember that although energy systems models are created to help inform policy decisions, these models are often conservative in their projections for technology.

Pick ecosystems, not technologies: Instead of investing in a single form of technology, policymakers can be more effective by picking ecosystems of innovation and clusters of innovation that include many different approaches.[33] The US Department of Energy's Energy Storage Grand Challenge is one example of a comprehensive program to accelerate the development, commercialization, and utilization of next-generation energy-storage technologies.[34]

Support deployment, not just basic R&D: Climate-tech investors often want to focus on early-stage R&D. Although this phase is undoubtedly important, recent successes such as solar PV, wind, and lithium-ion energy storage have shown that the scale-up phase is essential for widespread market adoption. Governments should get involved early through subsidies, demonstrations, manufacturing incentives, public–private partnerships, and other mechanisms designed to support early adoption of emerging technology.

Create performance-based policies: Policies should be structured to reward technologies that succeed in performance metrics. For example, India is working to set R&D incentives around cycle life and energy density as part of its energy-storage mission.[35] In China, EV incentives are increasingly being tied to performance and cost-based attributes that become more stringent over time.[36]

Approaches for Businesses

Strive for rapid and continuous innovation cycles: Whether in product design, manufacturing processes, or new market opportunities, businesses should focus on rapid iteration and learning. Projects that take years to test and evaluate will move slowly down their learning curves or risk failing slowly as the market and competition continue to evolve.

Look for opportunities to leverage simple, standardized technologies: Simple, standardized technologies such as solar PV and LEDs benefit most from learning curves because of high production volumes. Customized, complex technologies, such as conventional nuclear plants, benefit far less due to slow rates of incremental production.[37]

Test and scale through corporate partners: Corporate partnerships can provide critical access to customer intelligence, manufacturing knowledge and capacity, lower-cost supply chains, established distribution, and demonstration projects, all of which can accelerate the path to commercialization for new products. This is true for innovation both among startups (e.g., battery innovators partnering with vehicle OEMs) and established firms (e.g., Microsoft and BP’s recent alliance to leverage their respective digital and clean-energy expertise).[38]

Anticipate supply bottlenecks: When new technology develops along a learning curve, new projections for deployment should signal future material needs. The learning curve for silicon PV was blunted in 2004–2005 because of a shortage of silicon. The rapid deployment of EVs has led to similar supply bottlenecks for lithium and cobalt.[39] Future technologies in industry, heavy transportation, and buildings may also require rapidly scaling supply chains.

Remain nimble or pursue market share: In technology areas where cost decreases are driven by advancements in exogenous technology (such as breakthroughs in government labs), companies are best served by remaining nimble, avoiding long-term contracts, and maintaining multiple suppliers. In technology areas characterized by economies of scale, aggressive pursuit of market share will most rapidly bring costs down the learning curve.

Invest widely rather than deeply: Tech incubators often succeed by investing small funds in a significant number of concepts. Developing and deploying transformative climate technology will similarly require a greater variety and volume of concepts.

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22830 Two Rivers Road
Basalt, CO, 81621 USA
www.rmi.org