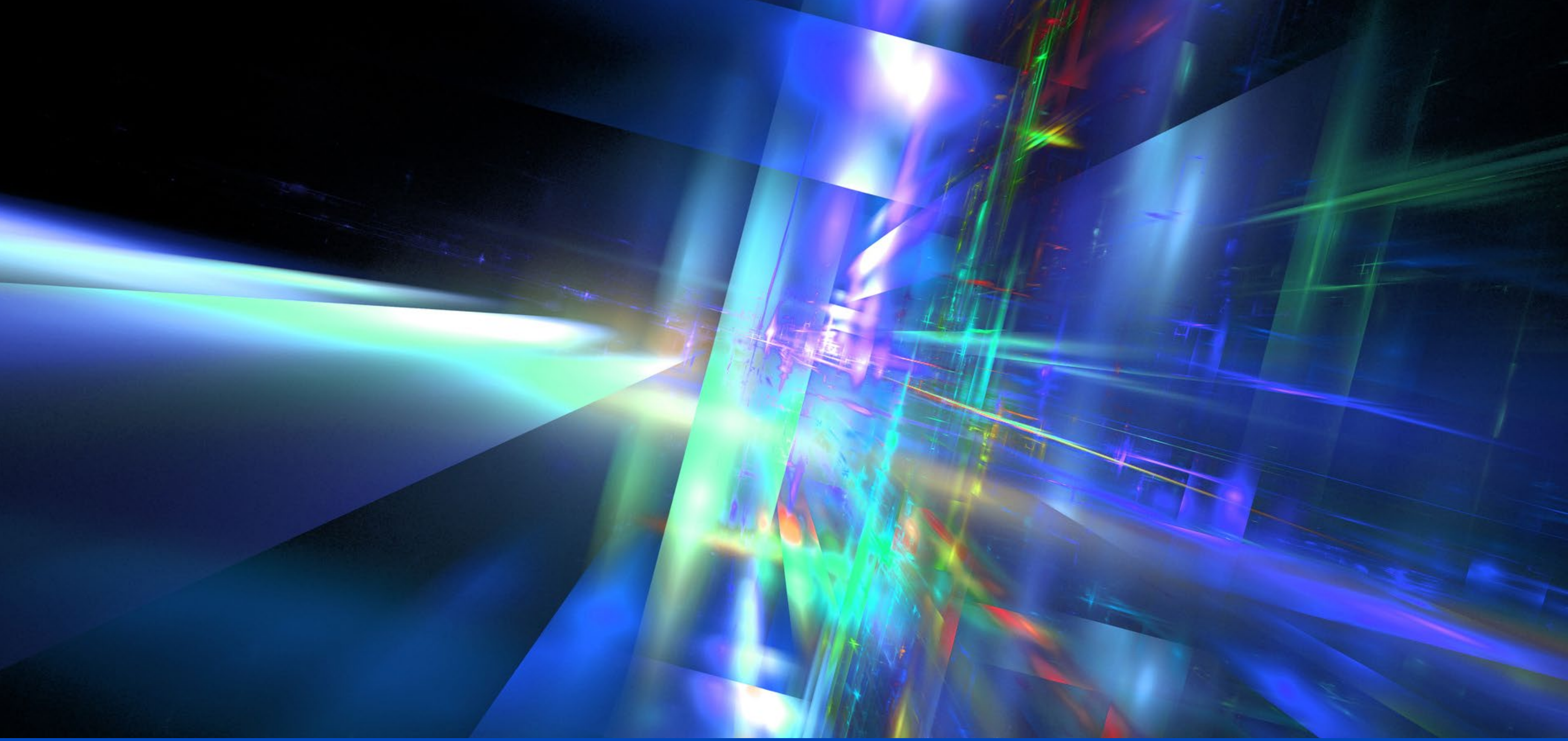

Restructuring Innovation for the Zero-Carbon Climate

Blueprint for an Innovation Technology Framework

CLEAN AIR TASK FORCE

February 2025

Forward

Climate ambition, at least on paper, has never been higher. After the 2015 Paris Climate Accords, more than 150 nations collectively responsible for nearly 85% of global greenhouse gases (GHGs) have committed to significant carbon reduction. Of these, nearly half have pledged to achieve net-zero carbon (74% of global GHGs), many by mid-century.[1]

Yet as we head towards 2050, an increasing number of observers question whether the so-called gold standard of 1.5° C can be achieved by that date or even soon after.[2]

This will require an energy system that is radically different from today's — one that is totally decarbonized. On that score history is not reassuring. Past energy transitions — wood to coal, coal to oil — have taken many decades, even after suitable commercial options became fully available. Worse, past transitions tended to support the resource mix of the status quo, rather than attempting to replace it with something new. And right now, new, zero-carbon options are in short supply. In fact, beyond variable renewables, few are ready to ramp up and roll out; and some, like fusion and deep geothermal, don't even yet exist.

In this Report, **Restructuring Innovation for the Zero-Carbon Climate**, Clean Air Task Force (CATF)[3] takes a fresh look at the new institutions, policies, and strategies — the *Innovation Technology Framework* — that we must construct if we hope to provide affordable, carbon-free energy at a scale equal to the climate challenge. Unlike analyses riveted to research and development (R&D), we examine the entire process through which new energy technologies achieve widespread use — from idea and R&D, through prototype and demonstration, to full-scale deployment culminating in market take-off. We do so for a simple reason: each new zero-carbon technology reaching the take-off point becomes another real-world clean energy option available to mitigate climate destabilization.

The four sections of this Report present the case for nurturing an array of these options, describe the historical evolution and maturation of major technological innovations, identify the elements needed to create a more intentional and structured framework for energy innovation, and describe the strategies and actions that will most effectively bring that framework into being. Our focus is on the global power, transportation, and industrial sectors, which collectively account for more than three-quarters of the world's carbon emissions.

CATF's approach to innovation policies flows from several baseline understandings. Central among them:

- To properly manage the risk posed by climate destabilization, we need to focus on developing a portfolio of low- and zero-carbon energy options — not just one or two;
- Existing strides in deploying wind and solar, though impressive, will not be sufficient to achieve a net-zero emissions world;
- New, clean fuels will be needed, especially in the transportation and industrial sectors;
- To fully manage the extreme risks posed by climate destabilization, major structural changes must occur in how governments and the private sector guide, coordinate, and promote zero-carbon energy innovation; and
- Decarbonization is not a one-and-done intervention; it is an essential effort to be maintained and managed over the coming centuries.

The primary audience for **Restructuring Innovation for the Zero-Carbon Climate** consists of policymakers, advocates, investors, and entrepreneurs in market economies. The Report is designed to help policymakers create an Innovation Technology Framework geared directly to the rapid development and deployment of a broad portfolio of cost-effective, zero-carbon energy technologies. As we explain, the key lies in re-orienting the energy innovation process to be more deliberative and interdependent, particularly during the period from initial research to robust market take-off.

This is a first attempt to describe an effective Innovation Technology Framework for energy resources. Although a restructured innovation framework will continue to be iterative and cyclical, the central insight, which we present as a set of best practices and policy recommendations, is that effective policy and institutional levers must be more carefully positioned to advance the formative stages of the innovation process. Much has been written about specific aspects of the innovation process, but relatively few publications discuss policy priorities during this formative period. We hope that this Report will help to fill that gap.

In researching this project, CATF convened a team of technical experts and industry veterans with extensive experience in the fields of engineering, finance, government research, development and demonstration (RD&D), energy start-ups, electric utility management, and public policy (brief bios appear in Appendix A). The nine-member team evaluated the institutions, policies, and strategies that currently shape technology innovation and commercialization; reviewed past policy choices, programs, and business plans; and identified new, cutting-edge approaches to technology design and project development. This Report grew out of the team's dialogue, analyses, and interviews, as well as an extensive literature review. CATF thanks each member for their important contributions.

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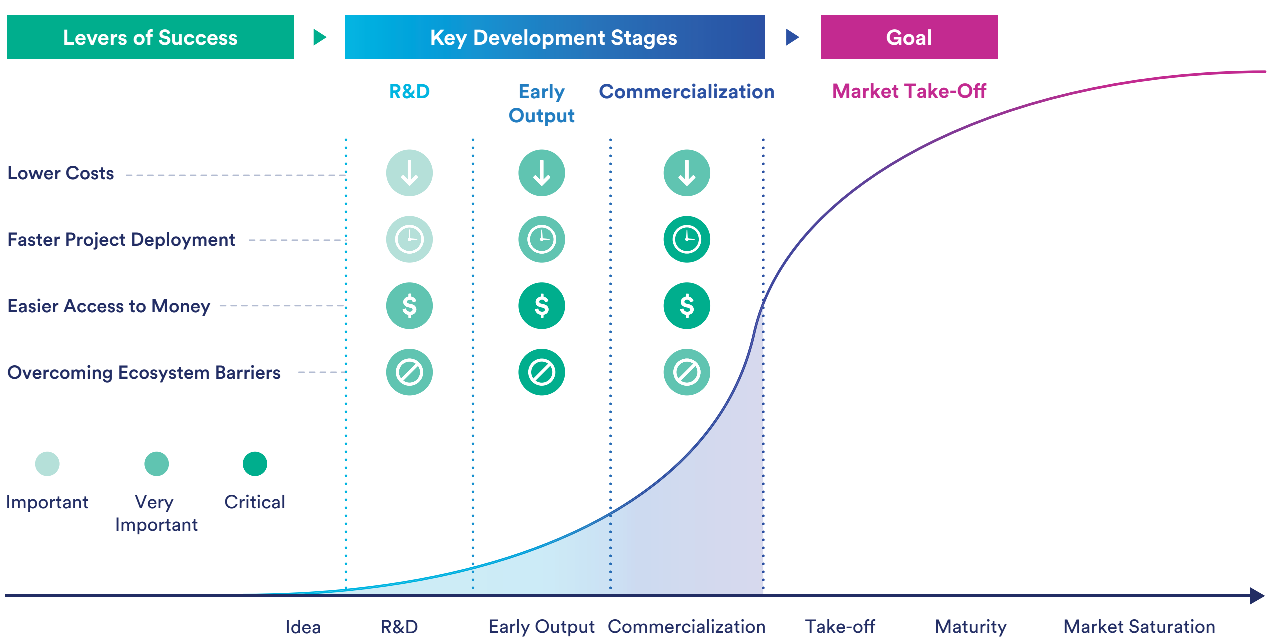
Executive Summary

Restructuring Innovation for the Zero-Carbon Climate sets forth an increasingly important but largely ignored strategy to address climate destabilization — the Innovation Technology Framework. When applied, the framework will accelerate the development and deployment of the essential range of technologies required to decarbonize the global economy to reduce global warming over the next century. These must include not just wind and solar, but also clean hydrogen, carbon capture and storage, nuclear fission, fusion energy, and superhot rock energy.

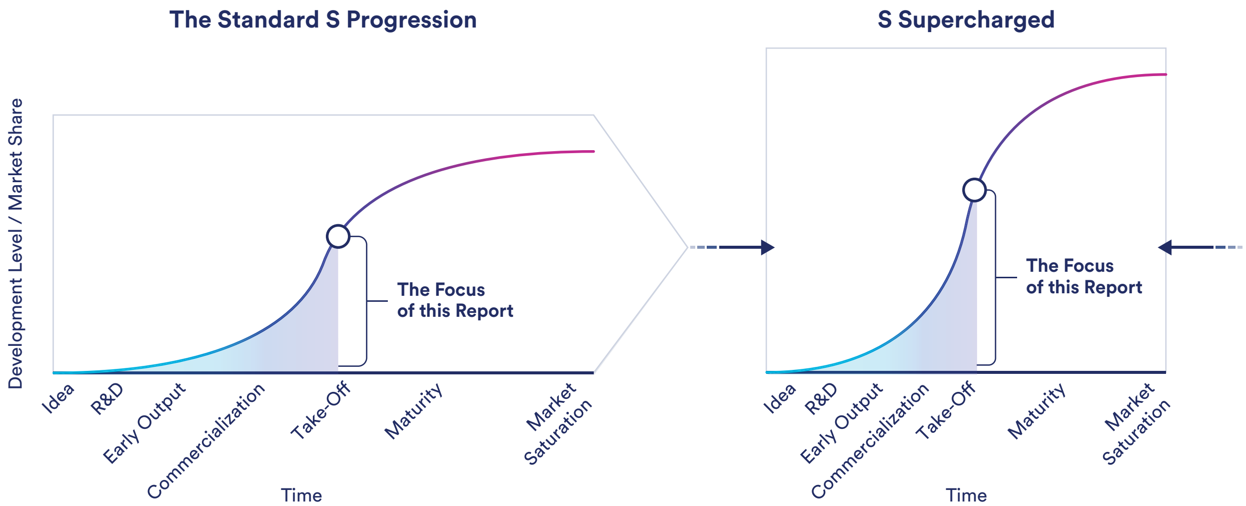
The Innovation Technology Framework presents the means to organize the massive policy response needed for full deployment of a mutually reinforcing set of decarbonized energy systems. This Report focuses on the innovation process as it unfolds — from idea to demonstration, and full-scale operation to successful commercialization.

Here, this process is conceptualized via the so-called S curve of innovation. Focusing on the most difficult period in that process — from R&D to take-off — the Report describes a framework for tailoring policy to a given zero-carbon energy technology's precise development stage – and thus speeding its market deployment. Key inputs range from direct government support to focused tax, financial, and regulatory incentives, which lead to stronger public-private partnerships and, ultimately, to a restructured institutional landscape. Together, they outline a new and much-needed industrial policy.

The framework identifies and designs inputs ("levers of success") that, at appropriate junctures in the innovation process, can lower costs, speed project development, ease access to financing, and remove barriers embedded in the existing regulatory and commercial ecosystem:



The overarching goal is to "compress the S" — that is, to speed and deepen commercial deployment of zero-carbon energy technologies, particularly those in the early stages of development:



Central to the discussion is the need for a multi-pronged, portfolio approach to zero-carbon energy development. In Section 1 of the Report, this argument is laid out in detail:

- To maintain climate stability, carbon control must continue indefinitely — it is a problem to be managed, not "solved." The only way to effectively manage climate is to restructure the energy system — a project that must start now, as it will take decades.
- The optimal way to address risk and avoid path dependency is to develop multiple solutions at once, a portfolio approach. The number of options matters.
- Carbon-free, load-following, firm power is essential to supplement variable resources like wind power and solar photovoltaics.
- The global electricity system is projected to double over the next three decades, driven by greater electrification throughout the industrialized world and by continuing development of economies in the Global South.
- Significant sources of carbon emissions do not easily lend themselves to existing reduction technologies. These include heavy industry, aviation, international shipping, and regions not well-provisioned with sun and wind.

Sections 2 and 3 introduce the S curve, explain why its initial arc is especially perilous for new technologies, outline the Innovation Technology Framework's analytic approach, and provide several examples of existing zero-carbon energy technology options, locating them on the S curve and describing the current policy challenges they face. Those examples include the creation of hydrogen stations for heavy trucking in the U.S., the blending of ammonia into diesel fuel to propel marine shipping, and the development of a versatile test reactor to speed the evolution of advanced nuclear energy.

For each technology, this approach moves through five steps:

- Determining the approximate level of diffusion at which a specific zero-carbon technology would reach market saturation within a political or economic region by midcentury;
- Estimating the threshold at which that technology will achieve market take-off;
- Pinpointing where the technology or technology system is currently situated on the S curve;
- Identifying the levers of success essential to narrowing the width of the S curve and increasing its height. These would include more effective policies to be applied in the R&D, early output, and commercialization stages, as well as ways to address barriers specific to that technology; and
- Drawing on the innovation framework to highlight the types of policy refinements or additions that can advance the key levers of success.

Finally, Section 4 considers a broader set of precepts and conceptualizations designed to ensure that the Innovation Technology Framework maintains momentum over the long term:

- The pool of zero-carbon energy options must be expanded.
- From the start, innovation should aim toward its end goal: market take-off.
- The most challenging steps ought to remain the focus of the policy response.
- Policy tools should fit both the technology and its position on the S curve.
- Public/governmental financial support is essential right up to the point that a technology achieves take-off.
- Policy mechanisms must be simple, clear, and, at the commercialization stage, self-executing.
- Public communication should clearly differentiate between the demonstration stage and the development of full-scale options — with narrative built from on-the-ground examples.
- Success requires that key “ecosystem” barriers (systemic inefficiencies) be identified and addressed.
- Nationally, this transition will require business, finance, and government to apply industrial policy to innovation technology.
- Internationally, innovation policy requires integrated leadership from those nations, multinational institutions, and global corporations best positioned to move zero-carbon energy technologies forward.

Without a faster, more cost-effective, and more complete system of decarbonized energy development, we are unlikely to succeed in our long-term global effort to manage climate change. **Restructuring Innovation for the Zero-Carbon Climate** describes how an Innovation Technology Framework can succeed in managing climate change over the coming century.

SECTION 1

An Urgent Need to Broaden Technology Choice

Climate change's accelerating impacts and our collective inability to reduce greenhouse gas emissions are rapidly clarifying the need for a new approach to developing and deploying zero-carbon energy technologies — a suite of measures matched to the scope and scale of the climate challenge. This challenge is complicated by a pair of inconvenient circumstances: the strong likelihood that adequate worldwide response will occur later than is optimal, and the certainty that this response will need to be continuous.

The goal of this Report is threefold: (i) to show that continuous, long-term technology innovation must be an essential component of the global response to climate destabilization; (ii) to describe the dynamic pathways that can best incubate and deliver zero-carbon energy technology options ready to play a significant role in advancing that response; and (iii) to outline the key policy priorities and actions needed to conceive of, nurture, and achieve widespread use of these critical new energy technologies and supporting institutional systems.

This **first section** explains why climate change demands a diversified zero-carbon technology response. The **second and third sections** describe the structure of an innovation policy framework able to mount that response — first, in general terms; then, with specific examples. This policy framework connects and coordinates two over-arching components of energy technology development: (i) the nonlinear pathway that leads from idea to R&D, from pilot and demonstration project to initial product, and from full-scale operation to widespread global use; and (ii) a more intentional, carefully crafted set of policy actions which ensure that travel down this pathway is rapid, efficient, and effective. In concluding, the **fourth section** outlines policy priorities central to realizing the desired result: significant new zero-carbon energy options able to address escalating climate risk.

The Scope of the Problem

a few key numbers...

- Global GHG emissions have increased more than 50% since the 1992 U.N. Framework Convention on Climate Change, the foundational global climate protection treaty.[4]
- Currently, nearly 85% of global energy use is provided by fossil fuels — which in turn account for 80%-85% of total worldwide greenhouse gas emissions.[5]
- Atmospheric CO_2 had not exceeded 300 parts per million (ppm) for more than 800,000 years — until 1900. By May 2023, monthly average CO_2 was topping 423 ppm[6] – a rising volume that will take many centuries to reduce.[7]
- Global average temperature, already 1.2 degrees Celsius (2.16°F) above pre-industrial levels, is projected to reach 3-4 degrees Celsius (5.4-7.2°F) above those levels by the end of this century, in the absence of human action. Consistent with the 2015 Paris Agreement, the Intergovernmental Panel on Climate Change (IPCC) warns that the overall increase must remain below 1.5 degrees Celsius (2.7°F) during that period. Whether or not this goal can be precisely met, the risk of climate destabilization grows as time passes, carbon flows into the atmosphere, and temperatures continue to rise.

... underlining a massive global policy challenge

Central to this Report are the following data-based exigencies, summarized here and discussed in more detail later:

- To manageclimate change , we must control carbon emissions indefinitely — it is a problem to be managed, not "solved." And the only way to effectively manage climate is to restructure the energy system — a project that must start now, because it will take decades.
- Existing technologies are poorly positioned to address the full extent of the challenge. Variable renewables like wind and solar, even at large scale, are highly unlikely to accommodate the cyclical demands of future energy consumers.
- The optimal way to address risk is to develop multiple technologies. This portfolio approach helps to ensure that significant unknowns can be successfully managed. The number of viable options matters.
- The global electricity system is projected to double over the next three decades – driven by greater electrification throughout the industrialized world and by the continued development of the Global South. This makes it even more urgent to develop non-carbon-emitting energy resources.
- Significant sources of carbon emissions do not easily lend themselves to existing reduction technologies. These include heavy industry, air travel, international shipping, and regions not well-provisioned with sun and wind.
- Carbon-free, load-following electricity generation will be needed to supplement variable resources like wind power and solar photovoltaics (PV).

Delivering greenhouse emission reductions consistent with the reality of this ongoing challenge cries out for major technical innovation — far more than simply doubling down on what currently works or even what now shows significant promise. Technical innovation, in turn, requires two fundamental inputs: tailored public policy and smart investment. The reason is that the global energy system is vast, complex, slow moving, and subject to myriad nonmarket pressures as well as pervasive market failures (tolerating unpriced environmental damage, for example).

The Scale of the Global Energy System

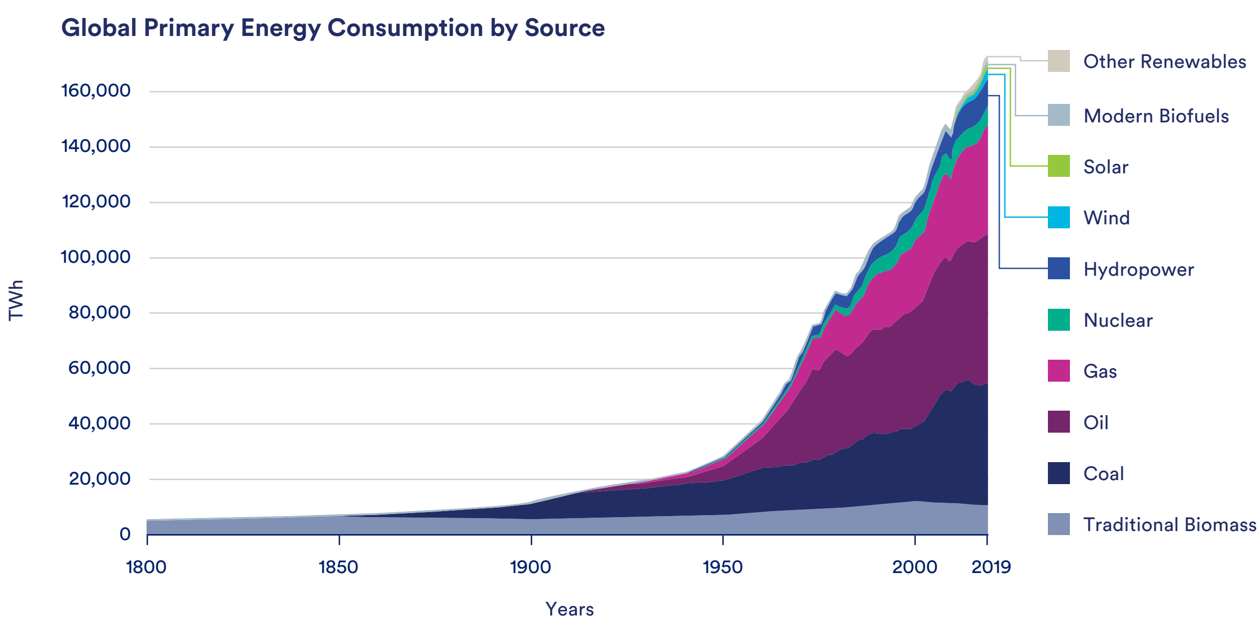
The energy system accounts for more than four-fifths of worldwide greenhouse gas emissions. Its major components are:

- Inputs (primary energy), now consisting predominantly of fossil fuels;
- Production of energy consumed by end-users (mainly electricity and gasoline);
- Transportation of energy via pipeline, vessel, vehicle, and electric transmission networks; and
- End-uses in vehicles, buildings, and factories.

As Figure 1-1 shows,[8] the global energy system right now is massively reliant on fossil fuels, despite recent, significant gains in the growth rate of certain variable renewables.

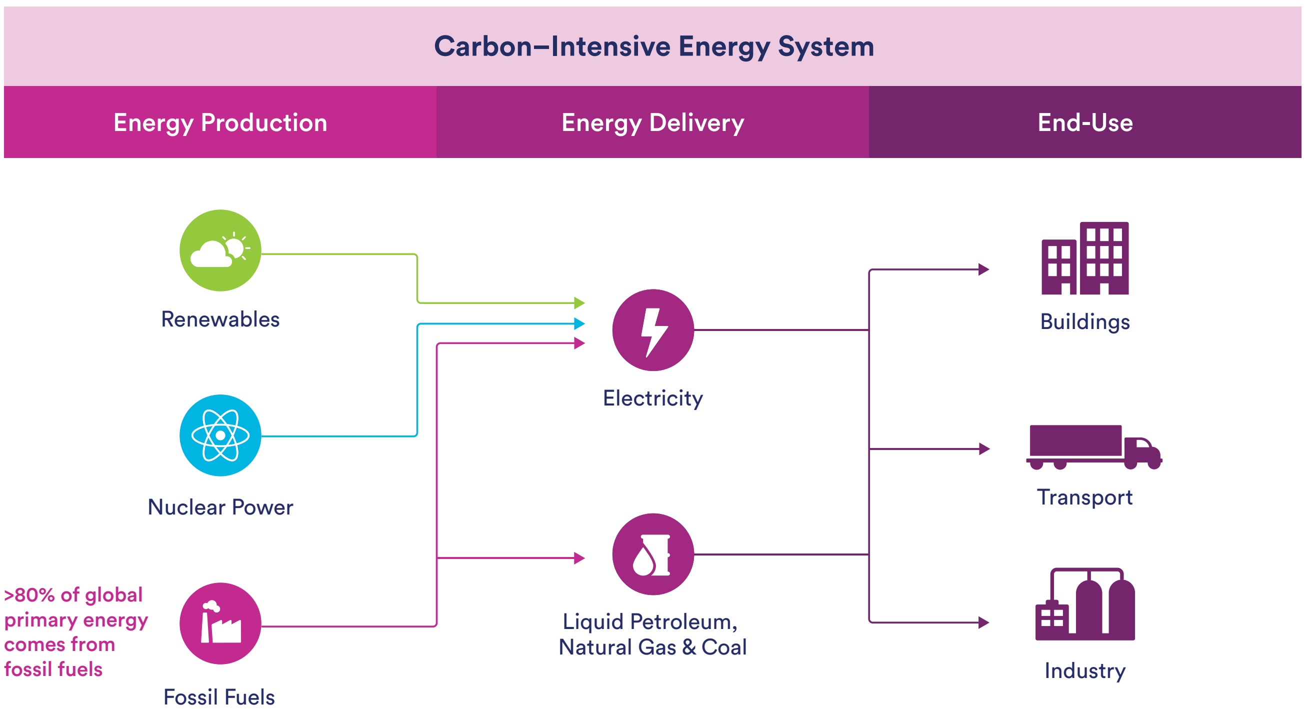
Figure 1-1: A carbon-fueled energy system

Source: Vaclav Smil (2017) & BP Statistical Review of World Energy



The following schematic shows how the system works today, although with sizable international variation in total energy production and relative contribution of inputs.

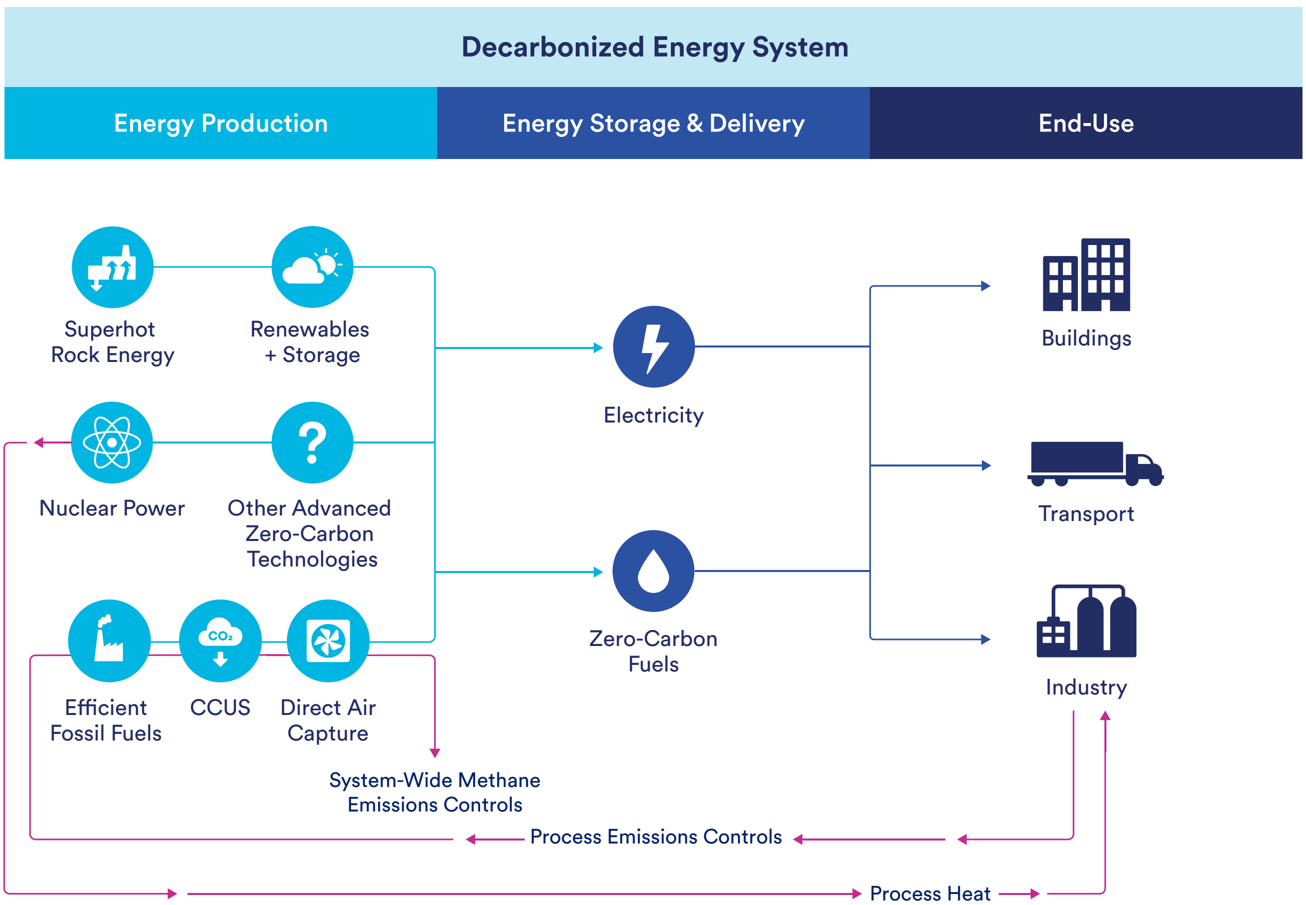
Figure 1-2: The world we have now



Although all components of the current energy system should and can become more efficient, the transition to a system that does not emit greenhouse gases (a net-zero or zero-carbon system) will require dramatic changes in the use of fossil fuels, the major source of primary energy today. Only then can levels of the two primary GHGs, carbon dioxide and methane, be reduced to near-zero, zero, or even net-negative — with carbon-capture technologies serving the subset of industrial activities that must continue to use fossil fuels.[9]

Such a system would look like this:

Figure 1-3: A carbon-free energy future



Currently, total global energy investment is just shy of $2 trillion a year (Fig. 1-4).[10] Of that, clean energy accounts for approximately $800 billion (Fig. 1-5).[11] To attain a net-zero world by mid-century, additional clean energy investment must reach at least $4 trillion a year by 2030, and remain at that level for the next two or more decades (Fig. 1-6).[12] A systemic transition of this magnitude will require global energy markets to commit to significantly greater investment in clean technologies at all levels of development, as well as to new and replacement infrastructure. Although in some regions markets are leaning in this direction, far more is needed if we hope to align capital flows with the scale of climate disruption.

Figure 1-4: Current global energy investment: Total

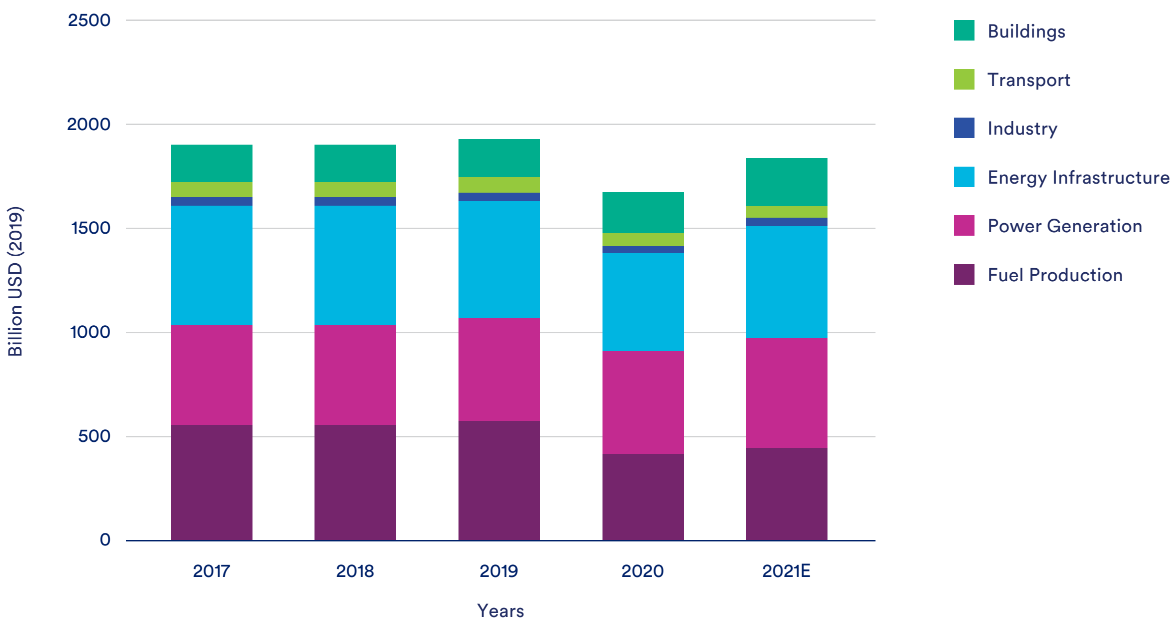


Figure 1-5: Current global energy investment: Clean energy

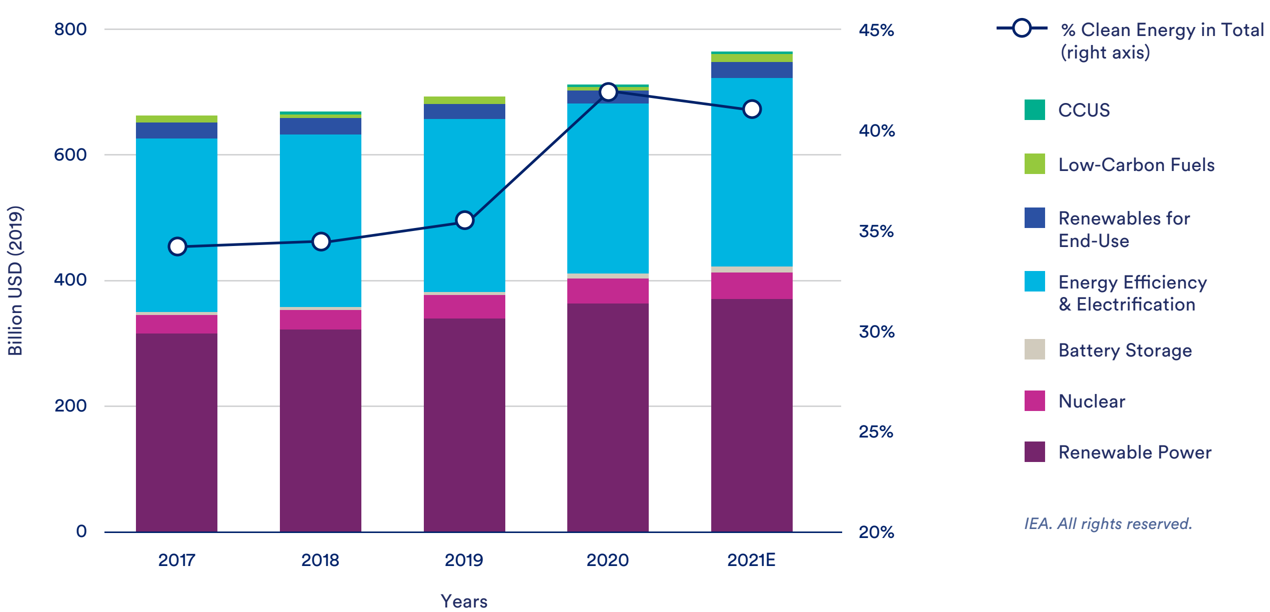
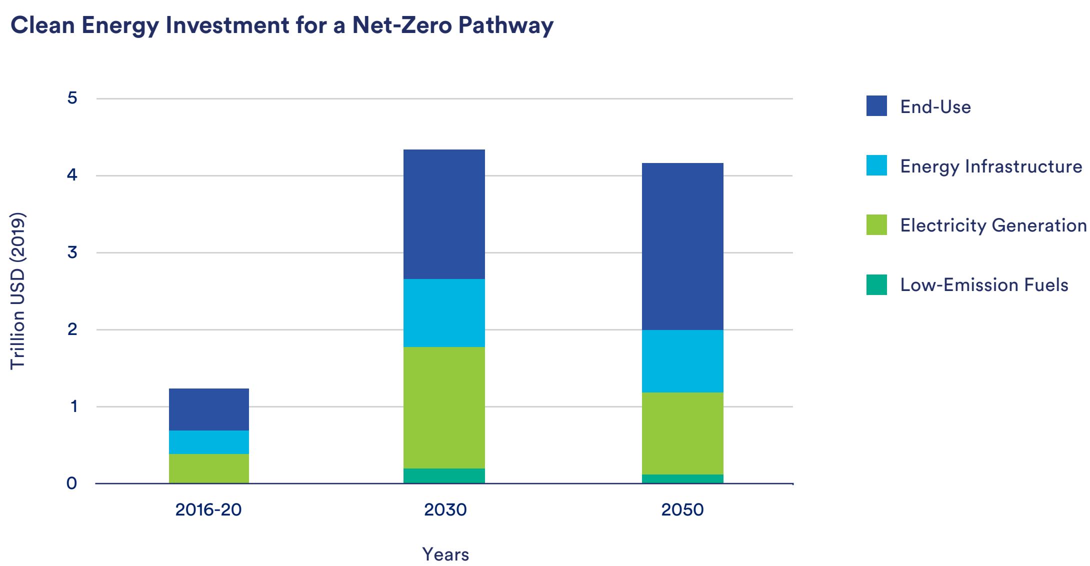


Figure 1-6: Needed Increase in clean energy investment, 2020-2050



Why Multiple Technology Choices Are Essential

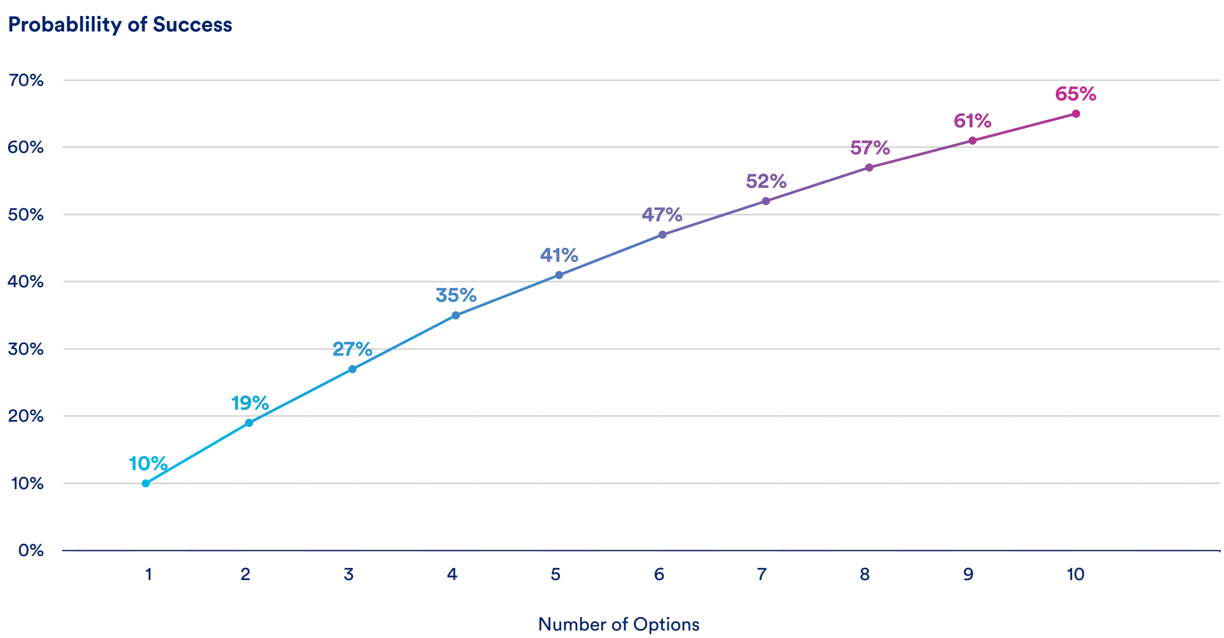
To decarbonize our energy system and reach net-zero emissions, leading analysts and nearly all major models point to the need to develop multiple decarbonization technology options over the coming decades.[13,14] Studies by the Intergovernmental Panel on Climate Change (IPCC)[15] and the International Energy Agency (IEA), as well as by other major climate research institutions, are in agreement. Supporting these techno-economic modeling results are six compelling arguments for significantly expanding today's truncated menu of zero-carbon energy options:

First, greenhouse gas control cannot end in 2050 or 2060. ***Our climate response must be continual.*** The only way to ensure that this happens is to restructure the energy system — a project that in the best of circumstances could take decades. That is, we not only need to start cutting carbon now, we also need reductions that will be effective over many centuries.[16] The technologies to achieve both of these goals are essential, but they differ. That is one strong reason to generate a portfolio of promising approaches, some of which can be implemented quickly (e.g., PV), while others, of necessity, must await further maturation — though they could play a key role later on (e.g., fusion, superhot rock energy). In short, part of the technology response must focus on long-term goals not likely to come to fruition for decades.[17]

Second, ***existing technologies are not well positioned to address climate change on their own.*** Renewables like wind and solar, even at large scale, are highly unlikely to accommodate the cyclical demands of future energy consumers. These intermittent (i.e., variable) renewables, which have been the primary clean resource additions over the past two decades, cannot easily address the ongoing need for large sources of instantaneously available, zero-carbon, and load-following power. The potential disconnect between supply and demand is certain to expand over the coming decades, as global energy consumption grows and the world becomes more reliant on electricity. Also, renewables are likely to encounter significant resistance, as siting issues intensify — involving both human and natural resource conflicts, as well as transmission limitations. Finally, if negative emissions — that is, actual reduction in the total level of atmospheric GHGs — must be achieved in the next few decades (as the most recent IPCC analyses conclude), sole reliance on wind power and photovoltaics will turn out to be an impediment. This is not to say that renewable development should be artificially restrained; rather, it means that much more than wind and solar will be required. In short, it's not either/or, but both/and.

Third, ***a portfolio strategy is the most effective way to address risk.*** That is, innovation is most likely to succeed if it proceeds along multiple pathways, providing multiple options. Technological innovation and market behavior are unpredictable, so relying on any single technology or a narrow range of technologies risks failure. A portfolio approach increases optionality and helps to ensure that significant unknowns can be successfully managed. As shown in simplified form in Figure 1-7, the probability of success improves significantly when a number of independent pathways exist. Here, if each of ten different technologies has only a 10% likelihood of success, the possibility that all will fail is cut in half. History has repeatedly shown that reliance on one or only a few technologies and approaches is risky or worse — particularly given that, at the outset, many pitfalls are not well-understood or even visible. Examples are legion: the public health impacts of coal and oil, the international economic and political ramifications of oil and natural gas, the cultural and demographic effects of hydropower, the economic and political challenges of central-station nuclear energy — even the unfettered use of biomass.

Figure 1-7: How a portfolio strategy reduces risk, in brief

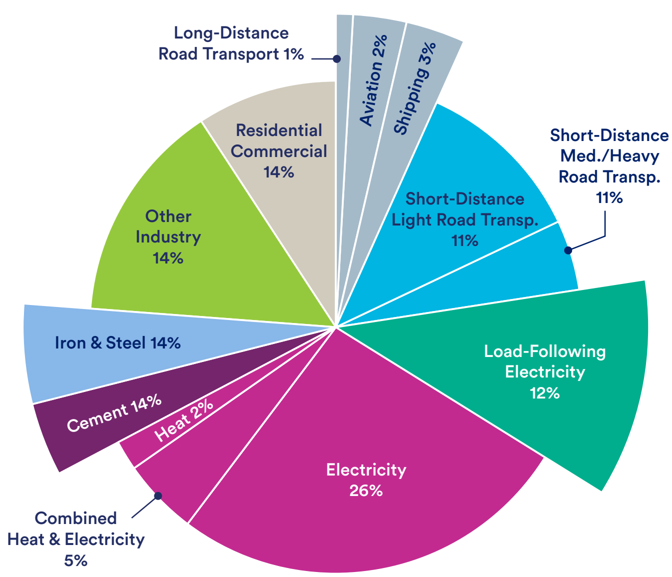


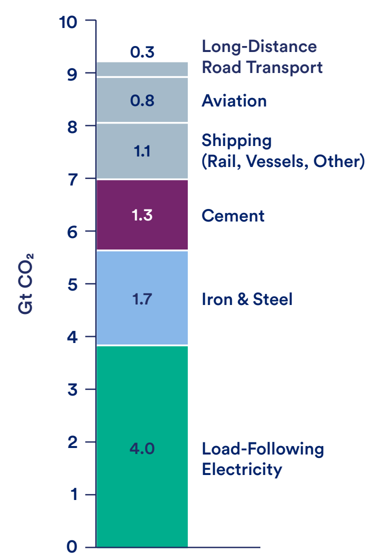
Fourth, as noted, the global electricity system is projected to more than double over the next three decades.[18,19,20] This follows for a variety of economic and technical factorss, particularly electricity's far greater efficiency, its adaptability, and its cleanliness at point of use. Indeed, electrification and decarbonization go hand in hand.[21] However, ***rapid growth in electricity demand places even greater urgency on the development of alternative, non-carbon-emitting resources as well as on the need to expand the available electricity grid.***[22]

Fifth, new, carbon-free technologies are needed because ***significant sources of carbon emissions are not easily adaptable to existing reduction approaches.***

These include heavy industries, aviation, and international shipping, as well as entire geographic regions not well positioned to take advantage of sun and wind (see Fig. 1-8[23]).[24] Particularly key will be development of zero- or low-carbon, energy-dense fuels. These fuels are more versatile than batteries and able to power transportation modes that require compact, light, and clean sources of energy. Right now, prime candidates include hydrogen (H_2) and ammonia (NH_3). Also important is that each region and nation, in possessing its own blend of natural resources, faces a varied array of structural challenges. This reinforces the argument that there will not be a single energy transition along a single pathway; rather, each jurisdiction must be able to define the path that best suits its geographic, political, and economic situation. In short, a range of solutions is needed to meet varied energy components and activities, as well as a broad spectrum of temporal, geographic, and climatic conditions. Fortunately, this regional approach integrates well with a technology portfolio strategy.

Figure 1-8: Energy and industry sectors from which GHG emissions are difficult to eliminate (27% of global total)





Finally, ***carbon-free, load-following electricity will be required as a significant supplement to variable resources*** like wind and solar, particularly in parts of the world that lack them or that reach peak demand when these resources are not available. Right now, much of the world's existing baseload power emits carbon. In some regions (e.g., Asia) the number of high-emitting plants, particularly coal-fired units, continues to expand.

There is strong support among modelers and other energy experts that dispatchable electricity is essential for meeting the zero-carbon goal.[26] Dispatchable electricity will also be required at the power-system level to integrate supply and demand technologies into a resilient whole. Naturally, all baseload power must be carbon-free.[27]

Why New Clean Tech Will Arise Only from Coordinated Innovation

An intentionally designed, climate-forward innovation policy can accelerate the development of new, better, and cheaper zero-carbon technologies — compressing the lengthy uptake period that, historically, new energy systems have required.[28] Coal took a century to catch on. Nuclear energy, three decades — and, even then, without quite doing so (see Fig. 1-1, above, and Fig. 1-9,[29] below).

During this time, the design and implementation of energy innovation policies have largely not been intentional processes. The same observation applies to our response to climate change. There, policies also have been piecemeal, with R&D at times mistaken for implementable innovation. Recently, the International Energy Agency warned that, "of the 46 technologies needed to address the climate crisis, only six are advancing on track for mass deployment to enable net-zero emissions by 2070 and restrain global warming to below 2° C."[30]

Figure 1-9: Big central-station nuclear — global expectations vs. global reality

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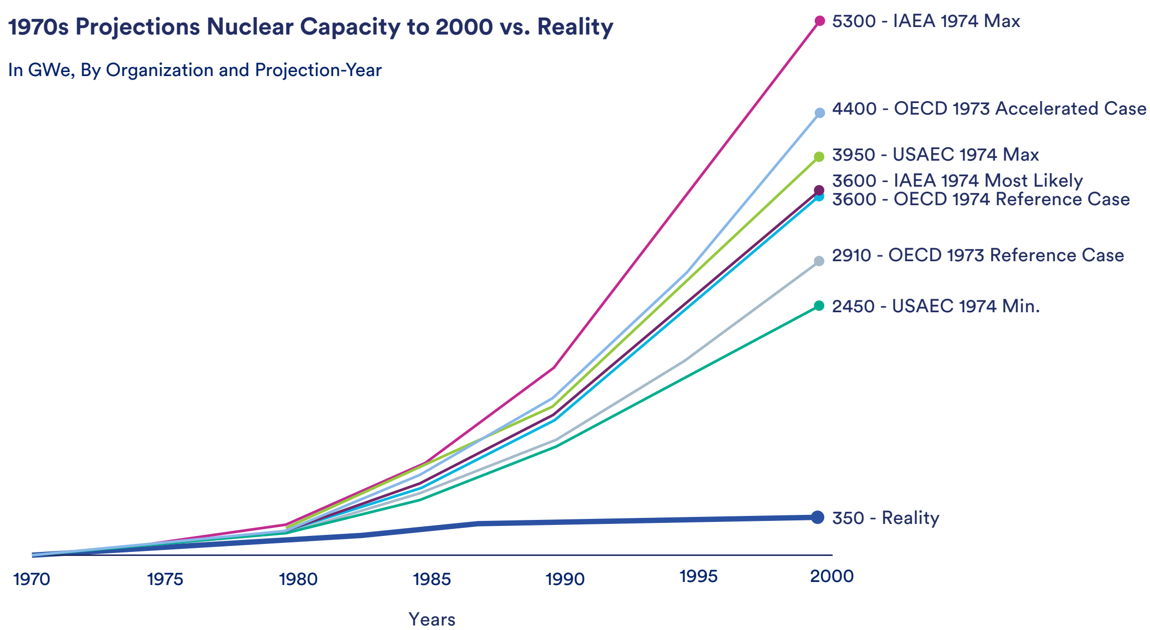


A coordinated innovation framework for zero-carbon energy is urgently needed for three fundamental reasons:

- ***The proximity of the threat.*** Historically, energy transitions have taken many decades. The shorter we can make the process, the more we can avoid or mitigate the impacts of climate change.
- ***Fatal incompleteness of traditional innovation programs.*** These programs tend to end with R&D before they achieve a firm foundation that includes some market acceptance and a higher degree of technical maturity. Without this foundation, large-scale deployment of the technology will stall over time.

  Moreover, traditional innovation programs may not effectively gather, assemble, and reuse learning from past or parallel programs.
- ***Poor coordination among policies.*** There is broad recognition that so-called demand-pull programs (particularly regulatory directives such as carbon taxes, cap-and-trade systems, or renewable portfolio standards) will not themselves jump-start early stage technologies. Major supply-side programs — that is, coordinated zero-carbon technology initiatives backed by adequate funding — must also play a central role.[31]

An instructive, albeit modest example of the desired coordination involves renewable resources and clean energy standards in the U.S. Decades of support for commercializing wind and solar have increased the ambition of individual states and of power companies. As a result, utilities responsible for nearly half of the U.S. power sector's GHG emissions have made legal or business commitments to achieve a net-zero emissions power grid over the next several decades.[32] These government mandates and private commitments, in turn, are prompting industry, labor, and NGOs to push for a more effective Innovation Technology Framework.

It Should Not Hurt to Try

One point bears emphasis: Failure happens. It is to be expected — particularly when attempting to speed, plus steer, the transition of an essential and huge economic sector (in the U.S., energy accounts for nearly 6% of GDP). Yet, political memory seems to adhere only to the failures, leading to the perception that innovation policy is an expensive mistake. In the U.S., villains are long remembered: the Clinch River Breeder Reactor, the Synthetic Fuels Corporation, the Barstow Solar Power Tower, FutureGen, and several "clean coal" demonstration projects.[33] There is also Solyndra, supported by the American Recovery and Reinvestment Act (ARRA) of 2009.[34] Two years later, with its innovative solar module technology swamped by the competition, Solyndra collapsed, losing in the process some $530 million in federally guaranteed loans. But that is far from the whole story.

Although some focus on these examples, the truth is that the full ARRA energy program has been a significant success. Since its inception in 2009, U.S. Department of Energy's (DOE's) Loan Programs Office has lent or guaranteed more than $35 billion in loans and loan guarantees to clean energy projects; defaults have affected less than 3%.[35] Perhaps most serious is that the tendency to fixate on worst cases leads to a "recurring problem with … energy technology demonstration projects — that at some point the goal [is] to avoid failure." But when that happens, the entire point of innovation is lost. To be useful, demonstration projects must "reveal unanticipated obstacles" – meaning that these projects make progress, even when they fail.[36]

In fact, it has been suggested that the ARRA program "has been too risk-averse to adequately support technology demonstrations, rather than too cavalier in its selections." One lesson is that technology support beyond pure R&D is best provided by institutions not directly subject to political pressure. "The critical task," Richard Lester and David Hart note, "is to devise an innovation system in which multiple pathways can be pursued and failure is tolerable."[37]

The Fundamental Goal of an Innovation Technology Framework

The objective of the Innovation Technology Framework is to help develop a portfolio of clean energy technologies, some that scale quickly and some that deliver benefits over the long haul. To achieve this, clean technologies must reach market take-off, which is where market forces assume a primary role in expansion. How is this point (sometimes referred to as an "inflection point") identified and assessed? This is a critical issue for the innovation framework, and it is described in more detail in the next section. The short answer is that, while it varies by technology and region, a convenient starting place is 1%-2.5% of global energy demand.[38]

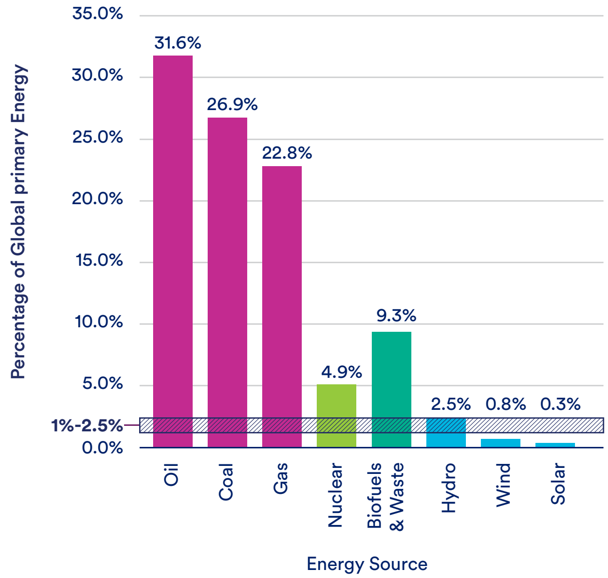
We believe that other equally valid thresholds may exist as well, including those that consider the length and strength of a given technology's growth rate, its impact on global greenhouse gas reduction, the achievement of a significant market share in a large number of nations (or, alternatively, in a few that drive global markets), wide use in places where reduction options are limited or the technology is unlikely to face major near-term competition, or significant uptake in a challenging submarket (e.g., aircraft fuel).[39] For now, though, the 1%-2.5% threshold serves as a useful starting point.

But reaching market diffusion can take time. For example, a 2009 study by Kramer and Haigh — which looked at the development of primary energy production technologies such as oil, gas, coal, nuclear, and renewables — found that, historically, technologies tend to take three decades to get there.[40] A 2016 study by Bento and Wilson focused on the deployment of a wide range of technologies (16 in total), including coal, gas, and nuclear units, steamships and steam locomotives, jet aircraft, washing machines, and mobile phones. They found that a 2.5% market share best signaled the end of the formative phase and the beginning of broader market availability.[41] However, they also noted that "the formative phases [of these technologies] are long, lasting an average of 20 years," before passing over an "adoption threshold" (e.g., market take-off).

Kramer and Haigh determined that, once an energy technology reaches threshold scale, an additional 30 years or so must pass before it accounts for 20%-30% of primary energy production, given the slow rate of system turnover and "the liability of newness."[42] Similarly, energy scholar Vaclav Smil found that coal and oil took 35 to 40 years to move from market entry to the control of a quarter of all primary energy production.[43] This research underlines the importance of multiple zero-carbon options — given that, even after take-off, a single option may capture only a slice of the market.

As Figures 1-1 and 1-10 indicate, coal, oil, and gas currently dominate the world's primary energy supply. Though energy markets are global, commercial thresholds for advanced technologies are first being reached in developed economies, such as those of OECD countries, or in large transitional markets like China's.

Figure 1-10: The threshold for technology take-off compared with global incumbents



Even though the 1%-2.5% threshold appears quite achievable in the context of existing sources (*see* Fig 1-10[44]), it is important to keep in mind that technologies can stall even after reaching this level of penetration. For instance, the current nuclear industry plateaued at 5% (*see* Fig. 1-9), experiencing only modest growth over the past several decades. To extrapolate: innovation policy must exist as an ongoing, evolving hub that sustains the global climate response. The way to create and maintain it is via an Innovation Technology Framework — or, to put it another way, through public programs that take their cues from "comprehensive industrial policy," albeit controlled significantly by the private sector.[45] The remainder of this Report will describe how that can be done.

Special Technology Challenges of the Climate Ecosystem

The development cycle of climate technology faces particular challenges. These underscore the need for a more coordinated and comprehensive innovation framework — one that can quickly generate zero-carbon energy options suited to the real world. It will be important to remain cognizant of these headwinds when designing policy to support that framework. They include the following:

- Energy is complex and interconnected, making coordination more difficult. For example, a seemingly positive initiative to increase sustainable biofuel may also cause land degradation and, ultimately, food shortages.
- Energy exists within an elaborate system — an ecology — that presents opportunities and barriers that must be accounted for if a given technology is to thrive. Hydrogen-fueled, heavy-duty trucks, for instance, not only require hydrogen, but also distribution systems, filling stations, and new vehicle designs.[46]
- Energy markets are overwhelmingly international, but international cooperation around energy is fragmented, at best. A zero-carbon future may become a topic of discussion between the West and China, given China's growing renewables industry and the health impacts there of coal. But zero-carbon's status in the EU, although substantial, is clearly not advanced by reliance on Russian natural gas.
- Existing technologies are deeply entrenched and powerful, given their years of dominance, their financial resources and political connections, their public profile, and the magnifying effects of natural monopoly and an often-too-cozy relationship with regulators. As one analyst puts it, new energy technologies typically "parachute into occupied territory."[47] The coal industry, for example, though in broad decline in the United States and Europe, retains the capacity to inhibit climate innovation in ways that extend well beyond its current economic footprint.
- Zero-carbon energy innovation often does not create a material product with strong consumer demand. Rather, decarbonization is a public good – that is, a benefit that individuals cannot own or monetize. It also is typically a benefit derived from a harm that's been prevented – and thus one that the public is far less conscious of. Indeed, given that this benefit likely will not become apparent for many decades, it may not even be visible to the current generation. The conundrum is worsened, of course, by the fact that much of the cost of the transition will be borne up front.[48]
- More than in other areas, zero-carbon energy innovation suffers from outside economic impacts, both negative and positive — the so-called "double externality problem."[49] On the negative side, it competes with many technologies able to artificially cut their prices because they are not required to pay for the massive health and natural resource damage their production inflicts.[50] On the positive side, firms know that some material portion of their effort will become a non-monetizable public good — and thus economically unrecoverable. This may be particularly problematic for risky, long-range technologies like fusion and superhot rock energy.
- Clean energy innovation historically has been concentrated in a few highly developed nations. Although this may offer efficiencies for rapid development of zero-carbon technologies, it also underlines the challenge of spatial diffusion — particularly the need to transfer clean technologies to nations in the Global South.[51]

SECTION 2

The Development Cycle of Technological Innovation

This section describes the stages that new technologies pass through as they move from scratchpad inspiration to significant economic reality. This conceptual model, as the final sections explain, must be accelerated globally through the coordinated operation of public-private institutions, policies, and strategies — especially along the path from R&D to market take-off.

A. The Stages in the Cycle

The existing literature examining this process varies in its terminology and, to an extent, key points of emphasis. But in general it describes an evolution that starts with an idea, passes through R&D and demonstration(s), reaches the point of commercial take-off, grows to "technical maturity," and ends with a stable slice of a given market.[52] Table 2-1 below lays out, as examples, parallel schemas from well-regarded, peer-reviewed studies that identify energy innovation's major phases.[53] The segment or segments that are the focus of this Report are highlighted in each.

In some cases, an appropriate set of policy actions and their desired results are attached to a specific phase. Some analyses assign to the initial step not only research and conceptualization, but also the creation of prototypes, testing and retesting models or components, fielding of demonstration projects (at least of relatively modular design), and, in a few, connecting to uncontested, niche markets. Historically, in the energy arena, this "era of ferment" has tended to continue for decades.[54]

Table 2-1: The various faces of innovation technology's multiple phases – in simplified form

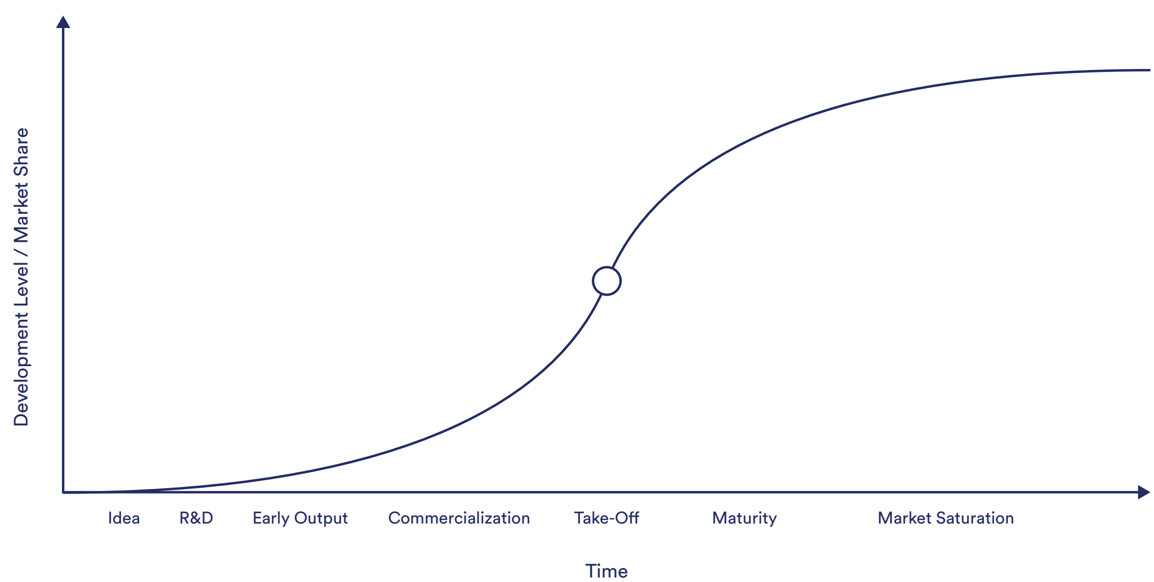
A	Technical Innovation →	Core Technologies →	Rapid Expansion →	Stabilization	
B	Invention →	Translation →	Adoption →	Diffusion	
C	Research →	Development →	Demonstration →	Market Formation →	Deployment/Diffusion
D	Emergence of New Technology →	Diffusion Through Markets →	Reconfiguration		

B. Introducing the Core Concept: The S Curve

The major goal of this Report is to outline ways to shorten the process of developing zero-carbon energy technologies and help those options achieve a significant market share as soon as possible. To better understand this, we focus on the so-called S curve of technology innovation — illustrated in Figure 2-1 below. The x-axis sets out the development phases we use here: the idea, research & development, early output, commercialization, take-off, maturity, and market saturation. The y-axis tracks technology development and, after take-off, market performance.

The S-curve is an essential conceptual model, one that is of particular utility during innovation's several developmental phases: R&D to full-scale product.[55] Later sections focus on the relationship between the shape of the curve and the pace of creation during a technology's initial period of development — from R&D to commercialization. But, right now, we take a quick look at the entire journey.

Figure 2-1: A very basic S curve for an individual energy technology



Phase One: R&D to Full-Scale Product

Most innovation support today concentrates on research and development. Given the need to create options and address hard-to-abate sectors of our energy system, a steady flow of new ideas and approaches is called for, particularly because most do not make it to market.

The R&D phase often starts with concept creation. The concept is tested at small scale in the laboratory and in the process refined. Constraints and opportunities that could affect commercial deployment may also be considered at this time. If the idea withstands initial testing and business model review, the project advances to the pilot or prototype stage. Here, it is tested at specially designed facilities or by adapting existing equipment. At the next stage — demonstration — the project is larger (if a plant or similar facility) and more developed, but still below commercial scale. Often, the scale chosen is the minimum required to persuade private investors that the technology is ready for commercial offering. Here, equipment integration and response under typical operating conditions are tested, along with expected wear over longer durations. Demonstrations provide the input needed to design full-scale plants. Finally, with major integrated products (e.g., advanced nuclear reactors), a number are built full-scale. This occurs during the so-called first-of-a-kind (FOAK) to Nth-of-a-kind (NOAK) stage, discussed in more detail below. (Other technologies, particularly modular components such as wind turbines or PV panels that can be created and assembled in bulk, follow a more streamlined path, but still face external challenges of the types discussed later in this Report.)

Phase Two: Take-off and Shake-out

The middle phase or phases focus on "take-off" and "shakeout," which are inversely related. At take-off, up-scaling starts in earnest. Here, growth accelerates — often far more rapidly than when the technology has matured and market demand approaches saturation. Shakeout describes how, among competing variations of a given product or design, one or a few become dominant. Total sales of the latter increase, sometimes with the help of niche markets, while unsuccessful competitors drop away.

The green dot at the center of the S curve, where the slope is steepest, constitutes the "inflection point" — really, a condensed range — at which this initial market incursion is most pronounced. It is also around this juncture that multiple reinforcing feedbacks flex their muscles and incumbent market occupants (e.g., coal and oil) fight back, often in the political arena. If the technology involves entire plants (e.g., a carbon- capture and sequestration facility), rather than component or modular parts (e.g., a new fuel cell or battery), the final deliverables may further increase in size as well as in number, with the FOAK-to-NOAK stage blending into market shake-out.

Phase Three: Market Diffusion

The last phase, sometimes called "materiality,"[56] ends with slow but widespread growth up to the point of market saturation. This final permutation can be seen as extending beyond market stasis to a broader, permanent transformation: in institutions, infrastructure, business models, user practices, and technical capabilities. These will be discussed in greater detail in Section 4 below. It is important to note that, for zero-carbon technologies, the market includes the full range of inducements, regulatory controls, and institutional actors existing in a given economy.

Wind and Solar Climb the Curve

Wind and solar photovoltaics are textbook examples of technologies that have started moving through the middle phase — rapid expansion or "take-off." In 2020, for example, global wind resources grew 53% over the prior year, the largest increase ever.[57] With China and the U.S. in the lead, annual added installed terrestrial wind capacity reached 92.9 gigawatts (GW), out of an end-of-year global total of 742.3 GW. For the decade ending in 2020, total U.S. wind capacity expanded by 203.5% — an annual average of 12%. Worldwide, the average growth rate was 14%. This was primarily the result of production efficiencies, including the use of larger turbines. From 1998 to 2020, rotor diameter of U.S. wind generators grew by a factor of 2.5 (from 50 meters to 125 meters), with the average nameplate capacity of individual turbines increasing by an average of 284%.[58]

A decade later, the same results were apparent in solar photovoltaics. In fact, from 2015 to 2020, generation of wind and solar accelerated globally at a compound annual average rate of 15%. If this were to continue, these renewable resources would provide nearly half the world's electricity by 2030 — and all of it by 2050.

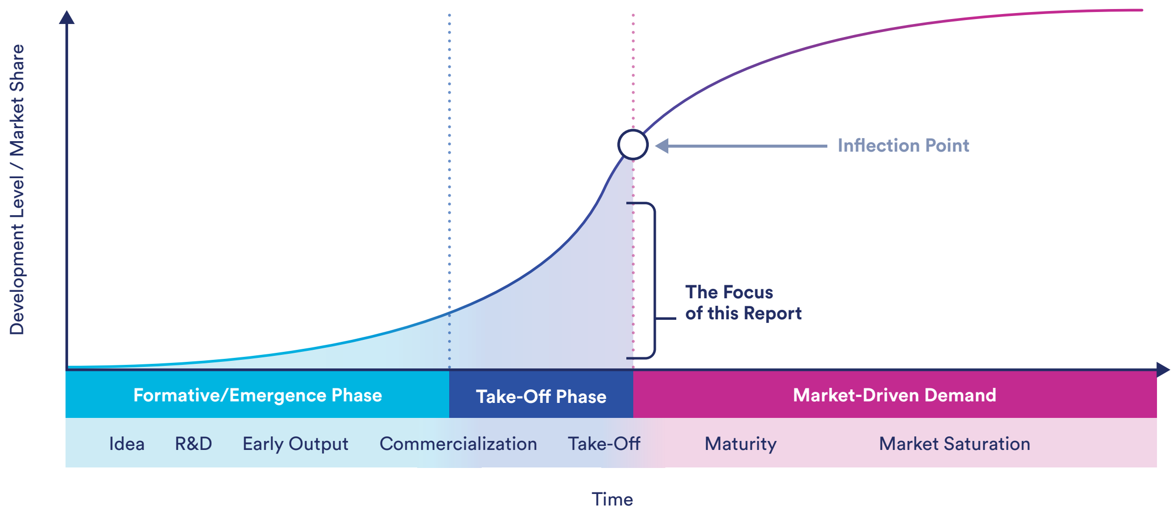
But that is unlikely to happen. Although wind and solar PV are moving up the steep part of the S curve, the rate of growth has started to level out. For example, a recent study found that, in nations where onshore wind and solar have reached technical maturity, the annual growth rate has stabilized at 0.8% and 0.6%, respectively, of the total electricity supply.[59] Unfortunately, in the aggregate, that adds up to about half of what will be needed to achieve a zero-carbon global energy system by mid-century.[60]

And this points to the need for three key advances: a stronger innovation framework to further stimulate wind and solar PV (and do so in more than just a few mature markets); a wider array of innovation beyond these successful renewable technologies; and clearer understanding that the move to zero-carbon must focus on the need to address a chronic condition requiring constant, long-term attention.

C. The S Curve as Model

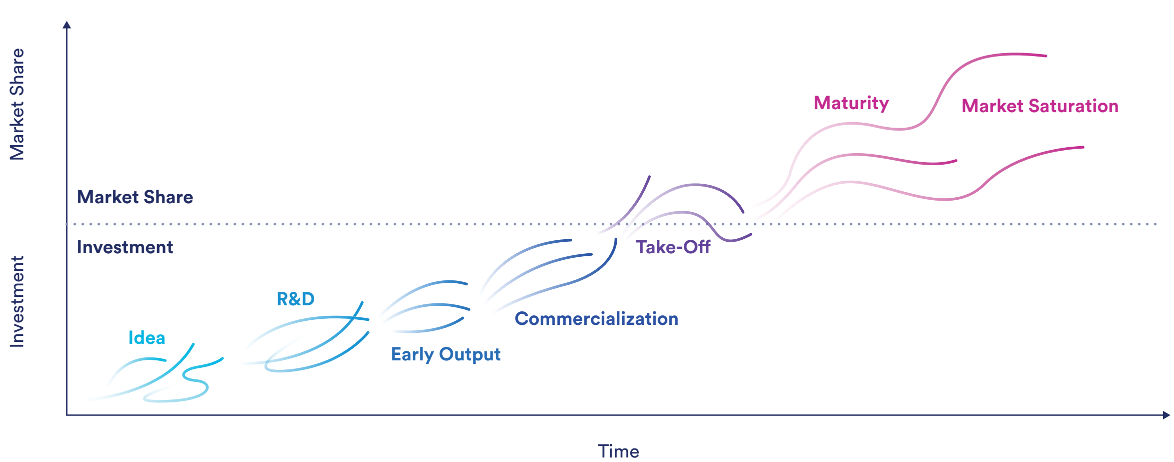
Strengthened by this brief background, we return to the S curve as the defining conceptual model:

Table 2-2: The winding path of innovation, along the S curve



Leaving aside variation in how component stages are denoted by energy experts, the idea of the S curve is central to the description and analysis of market innovation. At the same time, it's essential to understand that its conceptual replication in Figures 2-1 and 2-2 is far more linear (and singular) in theory than in practice. The following, though exaggerated for effect, points toward the way things work on the ground:[61]

Table 2-3: The winding path of innovation, real-world version — from idea to scale



In real life, elements of a given technology will exist at different points on the curve, while intermediate outcomes in the development cycle return as inputs into and affect the evolution of innovation at earlier points.[62] Moreover, related (and in some cases unrelated) developments that drive other S curves will influence the path of a given innovation, establishing sub-routines that are anything but linear. More broadly, a given technology exists in the context of other S curves of related products and plants — including potential and actual competitors. (The implications of this are further developed in Section 3 below and depicted in Fig. 4-1.) All of this must be kept in mind when considering how to accelerate the process of commercializing an effective zero-carbon energy system.

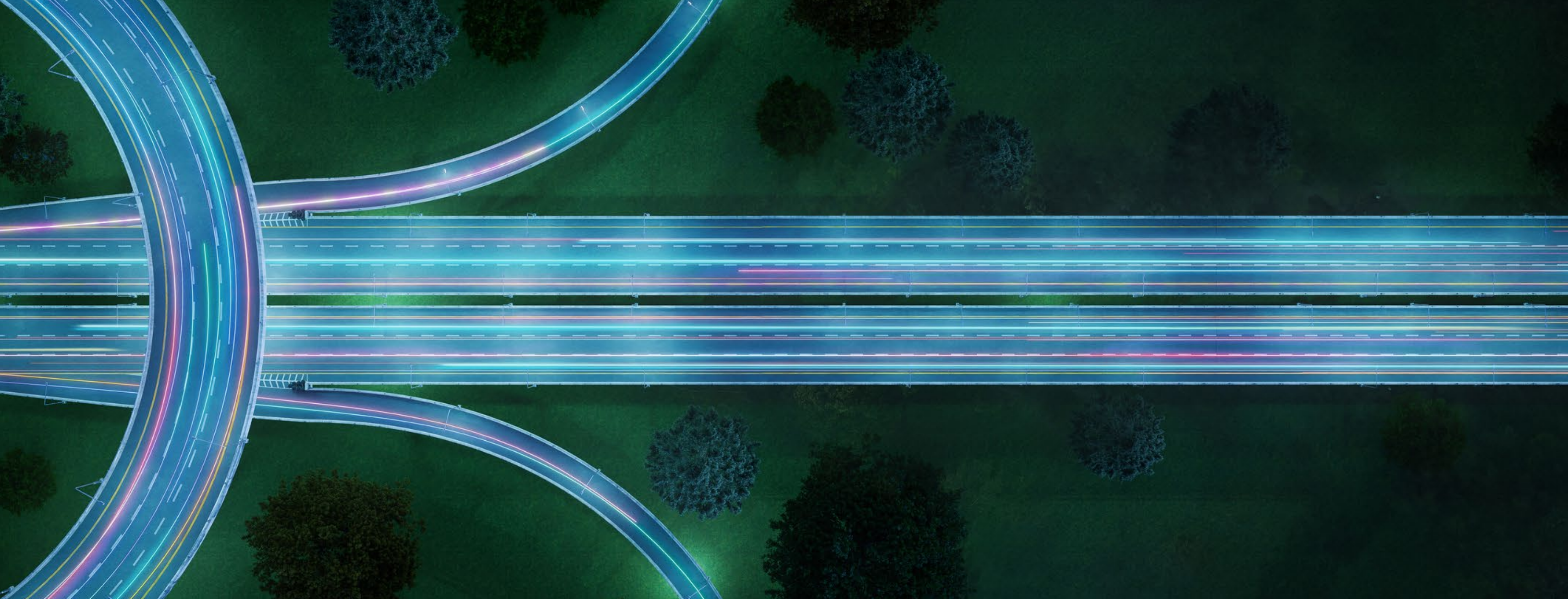
The Bigger Picture: Evolution of Energy Innovation Theory

In designing an effective Innovation Technology Framework, it helps to understand how innovation analysis has evolved since the middle of the last century.[63]

The initial analytic idea, animated by World War II technological success stories like early nuclear energy, was depicted in as a rising straight line. It was known as the “pipeline” model. There, technology invention moved in ordered sequence from applied research to prototyping, and from demonstration to widespread use, typically through market channels. This is essentially the pathway described in various ways in Table 2-1 above, if these stages were understood to be fully chronological and linear. Government-sponsored research and development propelled ideas through the pipeline. Although federal research did spin off valuable consumer goods (e.g., civilian air travel, the internet, smart phones, GPS, Google),[64] its central goal was to improve the public sector, particularly the military. The national government was the customer in chief.

In response to the limits of the pipeline model, a second, complicating concept arose, a product of economic analysis. Known as induced innovation theory, its proponents viewed technology and innovation primarily as creatures of private market forces. Seen through this lens, nations that led the world in new technology production were not necessarily as successful when it came to basic R&D; rather, their primacy arose from skill in linking market demand to new products, often ones that applied existing technologies in new ways. Example: Japan’s leadership in marketing smaller, more efficient vehicles in response to skyrocketing gas prices of the 1970s.

The third concept, prevalent today, builds on the first two, essentially by focusing on the dynamic structure and management of innovation, and on the institutions needed to guide it or in which it should take place. This concept accepts the pipeline model’s historical record of success, while acknowledging the power of market forces — effectively endorsing the utility of both in stimulating innovative technologies. But it goes beyond this by recognizing the importance — particularly in the international realm — of institutional supports and coordinated policies, especially ones that encompass the entire curve of technology innovation. These include collaborations with national labs (often as robust public-private partnerships), government and corporate research facilities, and academic institutions. This synthesis is a central element of the Innovation Technology Framework described in more detail in the next section of this Report.



SECTION 3

The Innovation Technology Framework: Accelerating the Uptake of New Technology Options

This section of the Report describes the Innovation Technology Framework and how to use it to shape policies and markets that ultimately drive the expansion of clean energy technologies. The framework is not a new law of science. It is not a sacred text. It is a model. As the renowned statistician George E.P. Box famously said, "Essentially, all models are wrong, but some are useful."[65] To the extent that the Innovation Technology Framework proves useful, it is because:

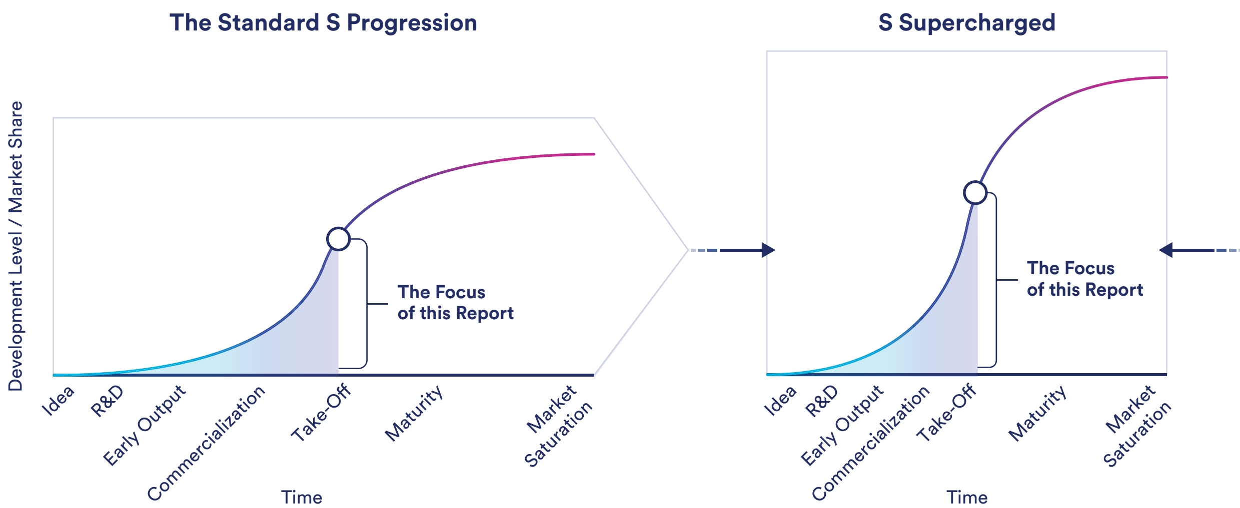
- The innovation framework focuses not just on improving the maturity of clean technologies but on ***supporting or creating industries*** necessary to deploy those technologies at scale. The central challenge posed by climate change is scale, and the failure to address that challenge is a major weakness of prior innovation policies.
- The framework provides a ***measurable target*** for innovation policies. Earlier, this Report noted that these policies often arrive piecemeal and are poorly coordinated, rarely reinforcing one another. But if we redesign and reimagine these policies, how do we determine whether the new ones are any better? The framework provides a metric: we compare them at the "take-off" point.
- The framework offers a simple but powerful way to identify the types of policy actions needed to ***reach "take-off."*** It identifies the four key factors that affect the shape of the S curve and targets those actions to the appropriate development stage of a given technology.
- The framework emphasizes the importance of developing and ***pursuing multiple policy options simultaneously.*** This aspect of the framework relies on our collective experience, rather than academic research. As practitioners, we understand how market forces, elections, court rulings, and natural disasters can change the policy environment. Thus, it is essential to keep options open, remain flexible, and seize new opportunities.

With that, our discussion of the Innovation Technology Framework returns to the S curve.

A. "Compressing the S"

What does a more effective climate technology path look like? Again observe the S curve, discussed in the previous section. Ideally, an effective technology option would move quickly through R&D, early output, and commercialization, soon reaching the "take-off" point, where the curve's slope is steepest. After take-off, it would rapidly achieve higher levels of market penetration. In other words, the width of the S curve would become narrower ("shorter"), as the period from idea to market saturation shortens. The curve would also become taller ("deeper"), signaling greater market penetration. The figure below illustrates the process of "compressing the S" in pursuit of accelerated optionality:

Figure 3-1: Accelerating the transition (shorter, deeper)



Our approach here — the Innovation Technology Framework — starts by considering the four key levers that influence the shape of the S curve and govern the success of the compression process. These "levers of success" are:

Lower Costs: If the technology costs less than other options, other things being equal, it is likely to shorten the time it takes to reach market saturation, narrowing the curve. Lower costs will also achieve higher market penetration, so the S curve will be taller (deeper).

Faster Project Development and Deployment: The speed at which the technology is created will help to determine the width of the S curve. For individual projects, that could mean shortening pre-construction and construction times. Multiple projects could be expedited by compressing the period between the completion of one project and the start of others.

Easier Access to Financing: This often determines the width of the S curve — that is, the speed of uptake. All e lse equal, ready financing shortens the path to market.

Removal of Ecosystem Barriers: Often affecting both the width and height of the S curve, these hurdles include inadequate supporting infrastructure and associated technologies; outdated, inefficient or overly complex regulation; misplaced public opposition; and weak or poorly focused policies and institutions. Clean energy technologies exist within a context of enabling technologies, know-how, government policy, and public alignment. If this "ecosystem" lacks key components or poses other obstacles, technology development will be delayed or derailed. (For more on ecosystem barriers, see Section 3.D.4 below.)

Table 3-1 below summarizes and provides examples of how these four levers of success influence the shape of the S curve.

Table 3-1: How the levers of success can advance technology deployment

LEVERS OF SUCCESS	IMPACT ON THE S CURVE	EXPLANATION	EXAMPLES
Lower Costs	Height & Width	Cheaper alternatives are deployed faster, with lower cost increasing the extent of deployment	Few new Gen III nuclear reactors in U.S., where cost exceeds $7,000/ KW. But, with cost under $3,000/KW, technology is still expanding in South Korea
Faster Project Development & Deployment	Width	The quicker the develoment, the steeper the S curve and the shorter the time to reach take-off	Modularity of wind turbine production accelerates project development time
Easier Access to Financing	Width	Timely access to sufficient capital speeds development	Higher first-project risk raised financing cost of carbon capture and sequestration (CCS) technology
Removal of Ecosystem Barriers	Height & Width	Overcoming key ecosystem barriers can speed deployment and optimize deployment level	**Width:** If deployment of CO_2 pipelines for carbon capture and sequestration stalls, CCS expansion will lag **Height**: Renewables penetration will slow as land availability shrinks

B. The Innovation Technology Framework

Although these levers of success influence the entire shape of the S curve, the Innovation Technology Framework focuses on their outsized influence along the lower arc of the curve, the period leading up to take-off (i.e., Phase 1, from R&D to full-scale product, described in Section 2 above). For clarity of analysis — and to better focus on specific policy interventions that create actual technology options — we present the initial sweep of the S curve in three stages:

- **Research & Development:** This period is often described in the literature in terms of Technology Readiness Levels ("TRLs"), which extend from TRL 1 (applied R&D) through TRL 9 (application under operational conditions). Though helpful in addressing aspects of innovation, the TRL methodology tends to gloss over a significant segment of the process — the crucially important span between early output and market take-off.[66] And it often ignores the set of structural challenges that typically present themselves early on in the process. As for policy support, the bulk during R&D is provided by direct funding and non-market financial incentives.

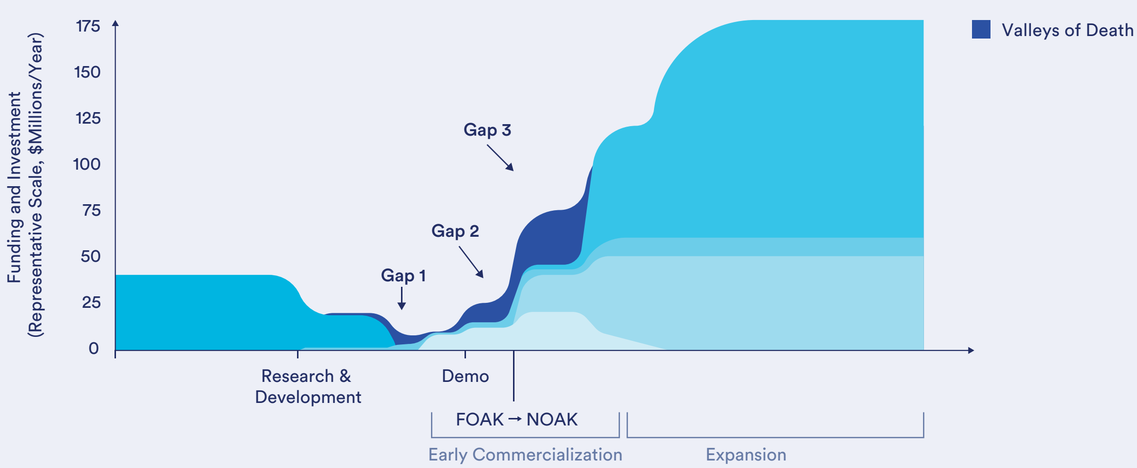
Particular Pitfalls: The Valley(s) of Death

One of the classic threats that new technologies of all types face is the so-called "valley of death" — actually, a triad of chasms (see Fig. 3-2 below[67]) — that can mark the untimely demise of a good idea. These are the quiet terminations of promising projects unable to obtain the funding or support they need to transit out of R&D, to advance from demonstration to commercial prototype, or to survive the commercial development process.[68] In the latter case, large energy systems generally will require several commercially-sized projects — starting with the "first-of-a-kind" (FOAK) and proceeding to the "Nth-of-a-kind" (NOAK). The details of moving from FOAK to NOAK will vary among technologies and locations, though typically for complex systems such as a carbon-capture and sequestration plant or a modular nuclear reactor, "N" can be five or more.

But sometimes even technologies that have been demonstrated at commercial scale — and have proceeded from first- to Nth-of-a-kind — are later dismissed as too costly or risky to survive in a competitive market. At the earlier, R&D level, a project may fail to progress due to a perceived lack of demand, or more basic concerns about cost or the ability to achieve scale. Even though many if not most technologies do not make it to market, they do require a more consistently supportive environment: first, because valley-of-death verdicts are inefficient (because the technology innovation process itself is inefficient); and, second and more tellingly, because, in the face of chronic climate disruption, a pressing need exists to bring a broader range of energy innovations closer to market without delay.

Figure 3-2: The three gaps at which failure is riskiest

Capital Investment Profile of a Zero-Carbon Energy Innovation



- **Early Output:** For technologies involving large plants, this period runs from the initial demonstration project to the first commercially viable plant (first-of-a-kind or FOAK), and then to a number of follow-ons (Nth-of-a-kind or NOAK) — a progression during which costs fall significantly and key ecosystem barriers are being addressed. But the FOAK-to-NOAK framework is less helpful when a technology relies heavily on factory construction of modular parts (such as solar installations), nor does it fit well when the goal is to convert an end-use technology like marine shipping or heavy-duty trucking to operate on hydrogen. For these reasons, we call this period "early output," a broader term encompassing the move towards a final product that, but for scale and infrastructure, is capable of competing in a robust market. Crossing the so-called valleys of death (see Box: Particular Pitfalls: The Valley(s) of Death) is the central challenge facing this phase. Here, much policy support is provided via technology-specific measures.

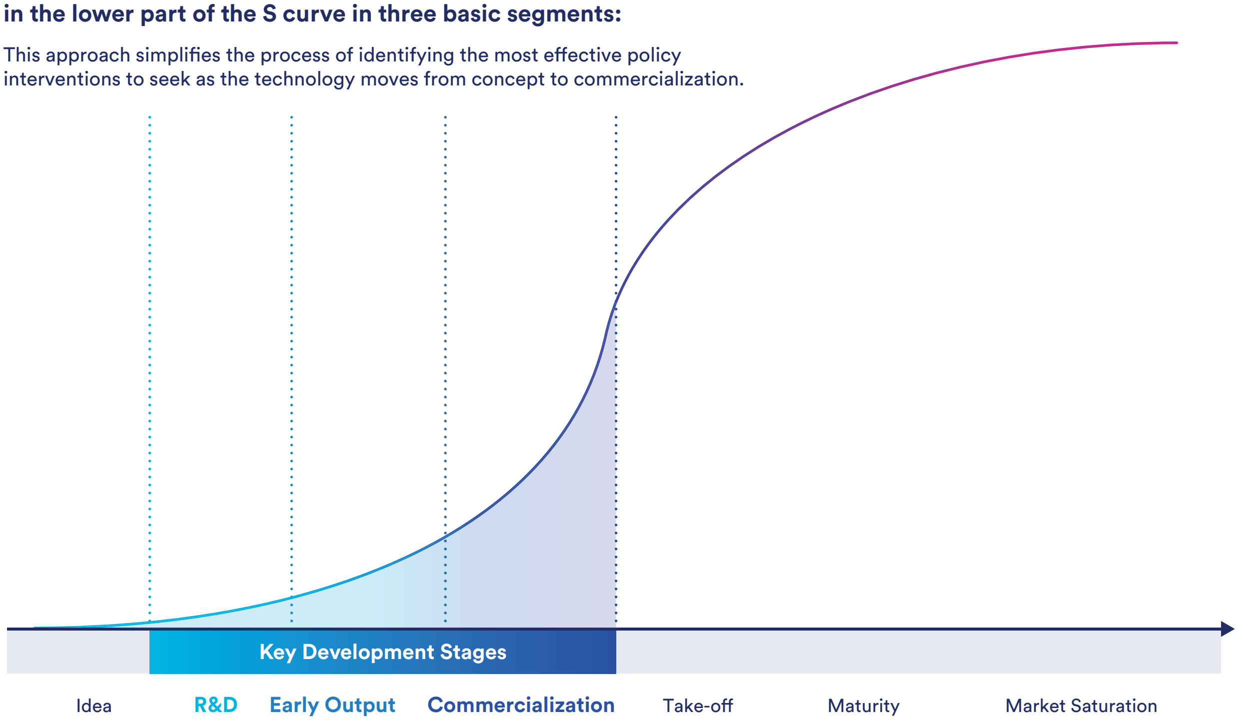
- **Commercialization:** This stage marks the period after initial costs have fallen significantly and commercial acceptability is climbing towards the "take-off" point. For central plant-based technologies (e.g., nuclear), this involves achievement of full-scale competitive models; and for all new energy technologies, it means that the key ecosystem barriers have been surmounted. At this point, a number of vendors are ready to meet market demand, based on standard commercial terms. At the policy level, technology-specific approaches have given way to more generalized inducements of financial markets and regulatory mechanisms.

Figure 3-3 below depicts these stages and how they relate to the S curve:

Figure 3-3: Key development stages in the context of the S curve

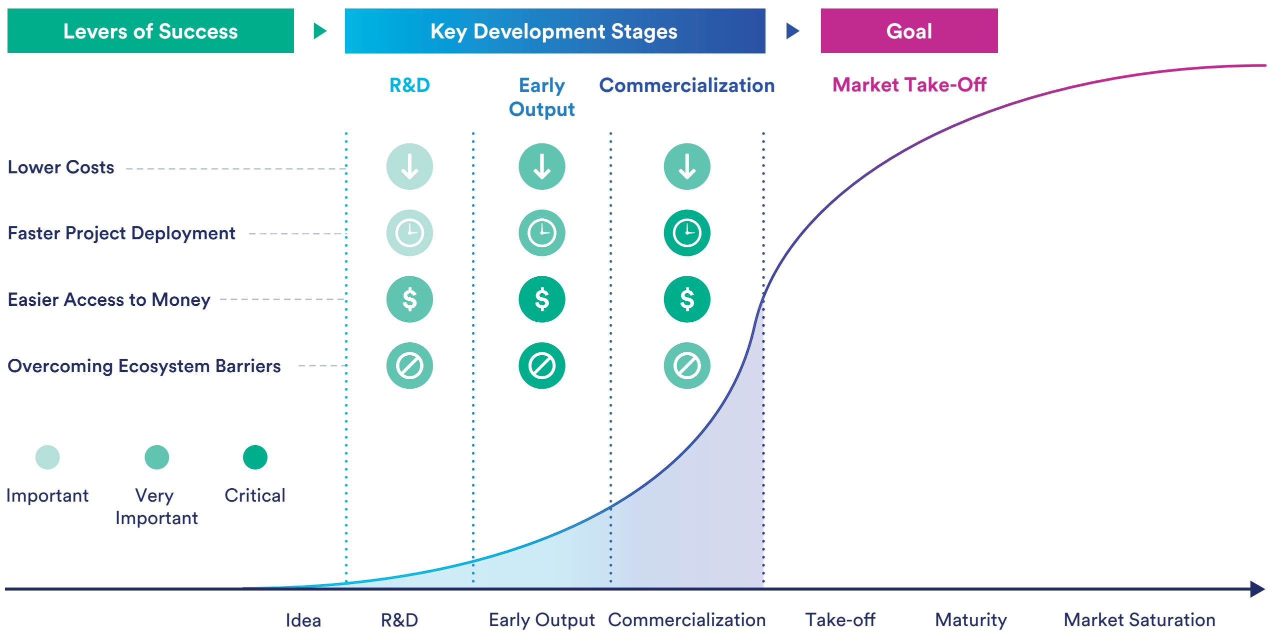
The Innovation Technology Framework analyzes the key phases in the lower part of the S curve in three basic segments:

This approach simplifies the process of identifying the most effective policy interventions to seek as the technology moves from concept to commercialization.



By adding the levers of success, the full Innovation Technology Framework comes into view:

Figure 3-4: Key development stages in the context of the levers of success



The left side of the innovation framework, labeled "development stages," focuses on interventions (policy-driven and in some cases technical) that tighten and deepen this section of the curve, starting with R&D, extending to demonstration projects or products, and ending with market take-off — generally at the inflection point along the steepest part of the curve. The reasons are twofold: (i) this stretch of the S curve provides the most significant opportunity to accelerate innovation; and (ii) success here exerts a strongly positive impact on the width and depth of the entire curve.

The levers of success identify the areas that can help a clean energy technology reach its full potential. These success factors may guide policies focused at the R&D, early output, or commercialization phases. Alternatively, they may assist in anticipating and circumventing roadblocks before they emerge. Note that different factors are more important at different stages, just as the nature of each may vary by stage. For example, lowering costs (in the form of subsidies) may be most critical for R&D, while removing ecosystem barriers (e.g., by creating a more effective licensing environment) may take center stage during commercialization.

The next three subsections describe the levers of success in greater detail, with particular attention to how they can advance technology development to more quickly maximize market saturation.

C. The Innovation Framework in Practice

1. Introduction: The Five Steps

Here we examine how the Innovation Technology Framework works on the ground. Informed by the discussion above, the framework is directly applied to a range of significant energy technologies capable of combating climate change. In the broadest sense, it is designed to clarify and condense the path forward as it moves through these five steps:

1. Determining the approximate level of diffusion at which a specific clean technology would reach S-curve "market saturation" within a political or economic region by mid-century. Often, a reasonable starting point can be derived from well-tested models that project technology needs under net-zero emissions scenarios;
2. Estimating the amount of the specific technology needed in the region to reach "take-off." To ensure it becoming a serious zero-carbon option, this would necessarily project the achievement of one or more intermediate deployment levels by given dates;
3. Pinpointing where the technology or technology system (e.g., hydrogen-fueled vehicles) is currently situated on the S curve;
4. Identifying, in broad terms, the levers of success required to narrow the width of the curve and increase its height, including the removal of barriers specific to that technology. The analysis also would consider whether more effective policies are needed at one or more of the following development stages: R&D, early output, and commercialization; and
5. Drawing on the innovation framework to highlight the types of policy refinements or additions that can advance the key levers of success identified in step (iv). Here, policy change includes actions by the public and private sectors, as well as those taken through international agreement, law and regulation, private compact and contract, industry standard, and institutional modification. Table 3-1 above points to the type and timing of policy changes that can be most effective. In Subsections C.2, E.2, and E.3 below, we examine specific examples in more depth.

Note that the Innovation Technology Framework is not itself intended to yield a detailed analytic blueprint for concrete action. Rather, it is designed to illuminate the pathway towards a more nuanced approach for developing an effective game plan to propel zero-carbon technologies toward optionality.

2. How the Technology Framework works: CCS as an Illustrative Example

To illustrate the framework, consider how it applies to the challenges of carbon capture and storage (CCS) in the United States, and how those challenges require the support of a redesigned policy framework.

The first steps of the framework seem simple enough — identify the technology's "take-off" and "market saturation" points. Doing that, however, requires expert judgment and careful examination of the industry as it now exists, as well as where it needs to go and how long it will take to get there.

In the United States, most of the CO_2 injected underground since the 1970s has been part of the enhanced oil recovery (EOR) process.[69] In Texas alone, over 800 million metric tons of CO_2 had by 2010 been injected and permanently stored underground using EOR.[70] But most of this carbon dioxide came from naturally formed underground domes; CO_2 from industrial sources was limited to sources offering inexpensive capture (for example, fermentation, which produces a high-purity CO_2 waste gas) or a capture step integral to the final product (e.g., natural gas processing). Furthermore, sources needed to be reasonably close to aging or disused oil fields. These limiting factors meant that as of 2020, carbon sequestration from industrial, non-EOR sources amounted to only some 13 million metric tons a year.[71]

Projections for future carbon capture and storage usage in net-zero emissions scenarios vary widely, depending on assumptions. Although analyses sometimes eliminate CCS in order to better understand the CO_2-reduction impacts of other technologies, the more robust models project the need for significant carbon capture and storage by 2050. For example, the 2021 Princeton Net-Zero America study estimated that, in two of its key scenarios, net-zero by mid-century would require that CCS in the U.S. annually remove about 1,350 million metric tons of CO_2 emissions.[72] Taking this as a proxy for market saturation, it indicates that the amount of carbon capture and storage must increase by nearly 5,000% over the next 30 years.

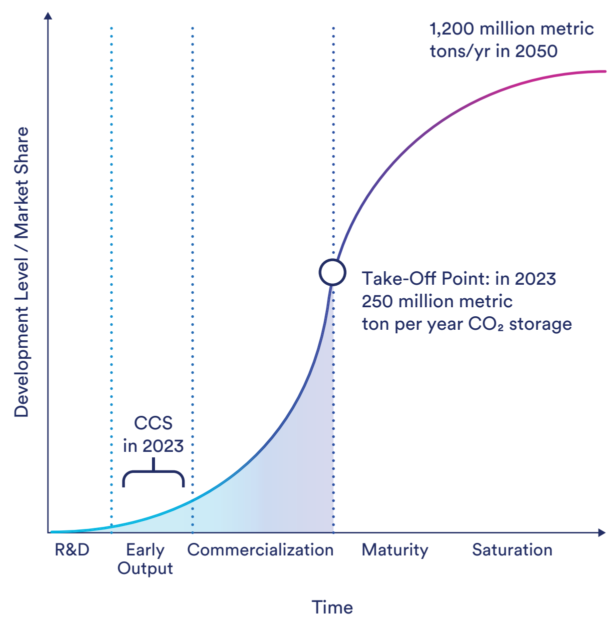
But the innovation framework takes a different approach, asking: What scale of carbon capture is needed, and when, to create a realistic *option* of sequestering 1,350 million metric tons by 2050? This implies that innovation policies should start with a smaller, intermediate CCS goal and reach it sooner. Later policies, derived incrementally, then help to drive carbon capture and sequestration to its mid-century objective.

The Innovation Technology Framework calls this intermediate goal the take-off point. What will prompt carbon capture and storage to become market-driven once it gets there? For CCS, the answer will necessarily involve some form of governmental encouragement — most likely, via regulation. Because carbon capture is a pollution-control technology that adds costs to a source, the probable driver will be a policy or policies that convince sources across the nation to install the necessary equipment. Policymakers must understand that carbon capture and storage technologies have reached a point at which regulatory requirements on that basis, for specific industries, are feasible and reasonable. In the case of CCS, the initial deployment push will be via incentives, first through R&D and demonstration funding, later supplemented by tax policy — with regulatory requirements coming into play in the 2030s. Current modeling and analysis shows a favorable ecosystem for CCS deployment, or take-off point, in the U.S. when sequestration reaches approximately 250 million metric tons a year.[73] This number is supported by analyses of the pipeline and storage network needed to maintain the option of meeting the later, mid-century target of 1,350 million tons.[74] It's worth underscoring several things about this estimate:

- Modeling a feasible take-off point is more successful if built on one or more intermediate levels supported by existing data. Here, the mid-term goal, as noted, is 250 million metric tons.
- The take-off point reflects assumptions about how the industry will grow. Being clear on this helps to identify a reasonable take-off point for deployment. For CCS, the premise is that incentives are driving growth in carbon capture and storage to the point at which regulatory requirements to reach mid-century climate goals become politically feasible. At this juncture, policymakers can take more direct action to reach those goals. This does not mean that emissions limits can't occur earlier in some sectors, but reaching take-off facilitates the development of policy options, while to some extent simplifying their application.[75]
- The definition of the take-off point in this example reflects the variant approaches discussed above, rather than defining take-off in terms of percentage of global energy market. The approach here is anchored in optionality. Reaching the mid-term goal and then proceeding toward the take-off point maintain the option of drawing on CCS to achieve mid-century, zero-carbon targets. Down the road, policymakers can choose to exercise that option or not.

The figure below shows where the take-off and market saturation points are situated in a general S curve for carbon-capture and storage in the United States.

Figure 3-5: The U.S. CCS curve — schematically speaking

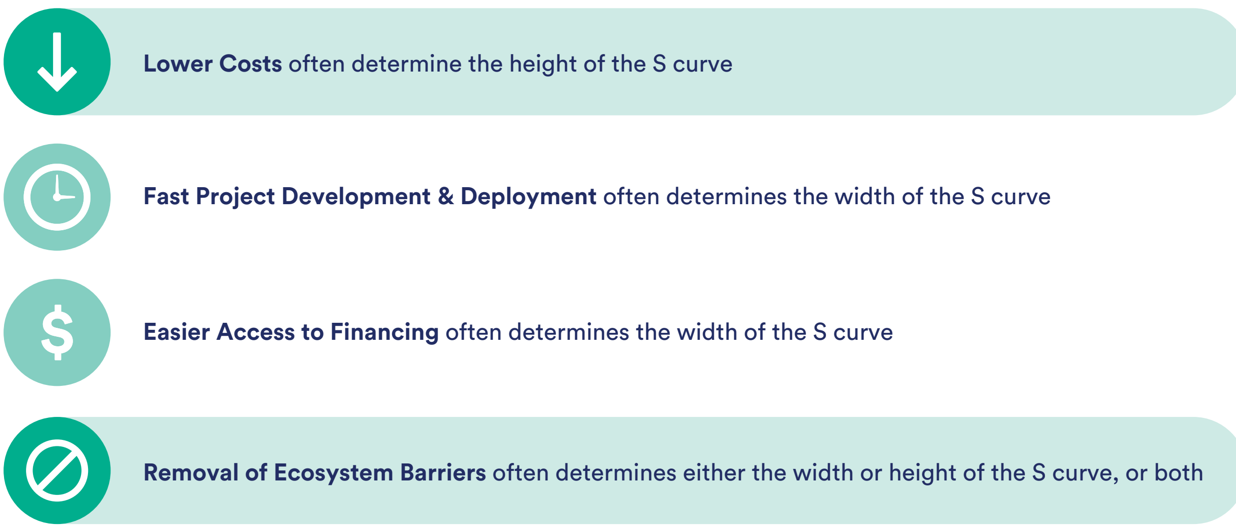


However, the S curve for carbon capture and storage is not as straightforward as the above graphic suggests. CCS represents three different technologies: capturing CO_2, transporting it through dedicated pipelines, and ultimately injecting and storing it deep underground. Each component is now at a different stage. Capture is commercially available for many industrial applications (for example, fertilizer production and gas processing), but is in the demonstration stage for others (e.g., integrated steel mills). Carbon dioxide pipelines are fully commercial and have transported over 500 million tons of CO_2 in the United States over the past 50 years. And storage technology is fully commercial for enhanced oil recovery, where it has been widely used in the U.S. since the 1970s. However, experience with saline storage is less extensive. In the context of deep decarbonization, it may be more helpful to consider carbon capture and storage to be in an "initial expansion" period. Innovation policies would thus be able to focus on two adjacent stages in the S curve — early output and commercialization.

Once S curve position is determined, the next step involves examination of the relevant levers of success best able to "accelerate the S." Although this receives greater attention in Section 3.D below, for now we consider the levers in terms of outcome. For CCS, the levers that are most significant are lowering cost and overcoming ecosystem barriers, as Figure 3-6 below illustrates.

At this point, the Innovation Technology Framework turns its focus to policy design. For this example, we focus on recent policy measures signed into law by President Biden that help to lower CCS costs and remove ecosystem barriers at the development stages of the S curve.

Figure 3-6: Highlighting the key levers of success



The 2022 Inflation Reduction Act (IRA)[76] includes several enhancements to the 45Q tax credit program that support carbon capture, including higher credit levels aimed at adapting CCS for hard-to-decarbonize sources in the industrial and power sectors. These provisions will help to lower carbon capture costs.

The 2021 Infrastructure Investment and Jobs Act (IIJA)[77] provides over $12 billion to support carbon capture, including $4.6 billion for CO_2 pipelines and saline storage sites. These provisions help to remove key CCS ecosystem barriers. These include insufficient CO_2 management, lack of front-end engineering and design (FEED) studies of CO_2 transport infrastructure, disconnect between existing injection well permitting regulations and the requirements of geologic sequestration, and need to overcome market resistance to products made with captured carbon.

For each of these important pieces of legislation, Table 3-2 below illustrates the links between development stage on the S curve and all four levers of success.

Table 3-2: How IIJA and IRA will activate the levers of success to spur technology development

[FEED = front-end engineering design (see Sec. 4 below); EOR = enhanced oil recovery, related to carbon capture and sequestration]

Details	R&D	Early Output	Commer-cialization	Lower Costs	Easier Finance Access	Faster Develop Time	Lower Ecosystem Barriers
Policy: Infrastructure Investment and Jobs Act							
$2.5 Billion: 6 demonstrations: 2 gas power, 2 coal power, and 2 industrial		X		X			
$937 Million: Large-scale pilots	X			X			
$2.5 Billion: Carbon capture storage hubs			X		X		X
$2.1 Billion: CO_2 pipeline finance support program			X				X
$75 Million: Class VI permitting		X	X				X
$100 Million: FEED studies		X	X		X	X	
$3.5 Billion: Direct air capture projects		X			X		
$115 Million: Commercial prizes	X			X	X		
Policy: Inflation Reduction Act							
45Q Credit value increase for direct air capture; $180/ton sailine storage; $130/ton EOR		X	X	X	X	X	
45Q Credit value increase for power industrial; $85/ton sailine storage; $60/ton EOR		X	X	X	X	X	
Reduce minimum capture tonnage requirement for 45Q		X	X	X	X	X	
Direct pay for first five years		X	X	X	X	X	
Extend construction start deadline for 45Q		X	X	X	X	X	

Together, these two federal laws will help to overcome a basic "chicken-egg" problem: companies won't invest in capital-intensive capture equipment without access to needed infrastructure (specifically, pipelines and storage sites) — but this infrastructure won't magically emerge; it must be built and ready to go. By simultaneously increasing the likelihood that both capture and infrastructure will be developed and deployed in parallel, the combination of the IIJA and IRA will help to overcome a major ecosystem barrier.

How do these policies measure up to the 250 million Mt take-off point described earlier? Over the next decade, the IRA is expected to lead to the installation of carbon capture technologies at hundreds of plants in the United States. Developed during the debate over 45Q enhancements, CATF's models estimated that, by 2035, the combination of IIJA and IRA could propel CCS to the take-off point. Other estimates developed after enactment of the IRA suggest that the impacts could be even higher. The Rhodium Group projects that by 2035 CCS will reach annual levels of 266 to 313 million metric tons,[78] while the REPEAT project estimates that the impact could be even higher — 450 million Mt/year by 2035.[79]

3. Adapting the Innovation Technology Framework

How should the framework analyze technologies that are in such early stages of R&D that choosing a take-off point seems especially problematic? This issue is particularly relevant to technologies like fusion, superhot rock geothermal, and some types of carbon dioxide removal (CDR).

Here, the framework is most useful when it focuses on ecosystem barriers. For instance, for fusion energy, the inquiry might consider whether some potential technologies will be more able to address radioactive waste barriers than others. For CDR, the question might be whether R&D can advance the verification and permanence of carbon dioxide reduction. By early use of the framework to address barriers to scale, nascent technologies can be better prepared to meet challenges expected to appear later along the S curve.

D. Levers of Success: How They Propel Change

Here we provide a more detailed look at how these four levers of success influence the key stages of technology innovation outlined above. This will help to identify the points along the S curve at which policy interventions that advance these success factors are most useful, and how those interventions can be most effective.

1. Lower Costs

The existing global energy system is enormous — annual investment alone now totals nearly $2 trillion.[80] Most of the future growth in energy demand will occur in emerging markets and regions, particularly China, India, the Middle East, and Africa. Most global population growth between now and 2050 (from 7.7 billion to a projected 9.7 billion) will occur in those markets.[81] Affordability will be a crucial component in rapidly developing nations, many of which have little economic wiggle room. This will also be the case in the OECD, where the existing fossil energy infrastructure is relatively low in cost, having been fully depreciated.[82]

How can innovation policy enhance the market competitiveness of new zero-carbon energy entrants? To understand this, we must examine several of the primary methods by which carbon reductions are achieved: research and development (R&D) focused on transformational innovation, R&D focused on incremental innovation, learning-by-doing, and economies of scale. Guided policy serves an important function in advancing each of these essential structures.

A recent study examined the dramatic decline in the cost of solar PV modules over the past 40 years. Examining data from 1980 to 2012, MIT researchers found that market demand-stimulating (demand-pull) policies like renewable portfolio standards (in the U.S.) and feed-in tariffs (in the EU) had triggered some 60% of these cost reductions, and that the total reduction could be allocated primarily among three key "high-level mechanisms": public and private R&D (59%), economies of scale (22%), and learning-by-doing (7%) — with R&D playing a stronger role at the beginning of the study period, and economies of scale becoming decisive in the later years.[83] (For more on push and pull policies, see Box in Section 3.E.1 below.)

Here, we take a closer look at three of these mechanisms — the first two of which involve R&D, and the third, learning-by-doing.

Transformational R&D invents new processes, materials, and methods that incorporate entirely different technology designs or approaches. Transformational R&D can significantly reduce costs, leading to a much lower cost end-point than would occur through production efficiencies created by economies of scale or (*see* Fig. 3-9 below) learning-by-doing. Combined-cycle natural gas power plants illustrate the impact of transformational R&D. Before this technology was commercialized in the early 1990s, steam turbines sometimes generated electricity using natural gas as a fuel. But gas was far more expensive than the coal that typically powered turbines. With commercialization of the combined-cycle process, however, natural gas became competitive with coal, due to the new technology's far higher efficiency. Further transformational developments, particularly directional drilling, reduced gas costs even more. Propelled by these innovations, gas power moved from being a niche market to becoming the dominant source of electricity generation in the United States.[84]

Incremental R&D reduces costs by adopting smaller changes that increase process efficiency, in contrast to measures that alter a major input, input source, or technology. Incremental R&D may result in a more modest downward shift in the cost curve or it may simply accelerate the benefits of learning-by-doing or economies-of-scale (see Fig. 3-9, below). Boiler efficiency improvements in steam turbines exemplify this type of change. More efficient boilers reduce emissions and costs, making plants more attractive economically, while lowering their lifetime environmental impacts.

Figure 3-7: Transformational research & development shifts the entire cost curve downward

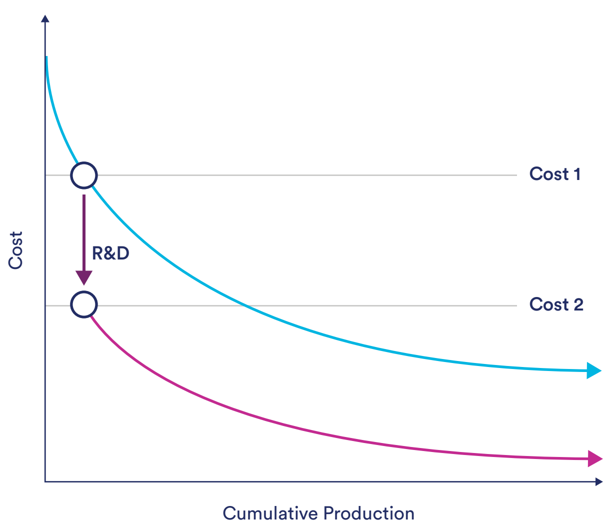
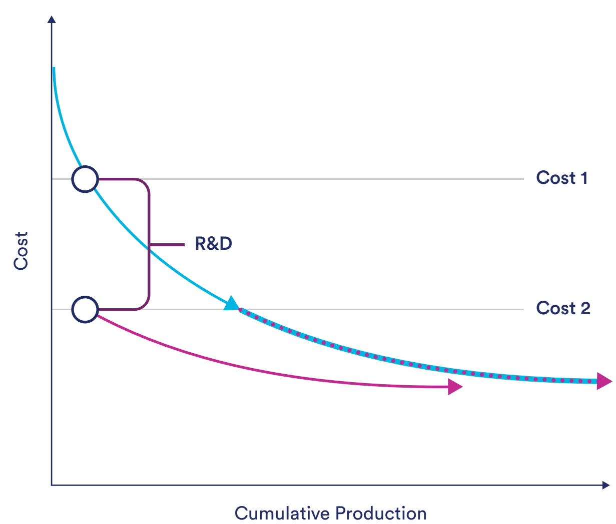
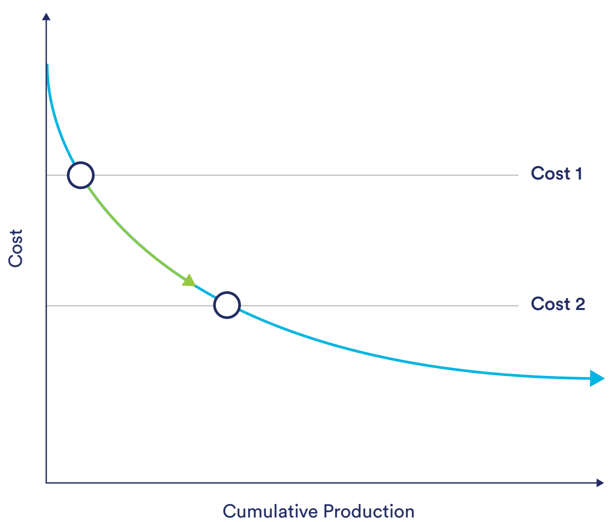


Figure 3-8: : Incremental R&D accelerates future gains by lowering costs from cost 1 to cost 2 without changing the cumulative quantity produced. Note that the shape of the dotted red curve is identical to that of the blue curve after cost 2



Learning-by-doing involves finding more efficient and cost-effective methods of manufacturing, designing, and deploying a given technology.[85] It occurs mainly up until the take-off point, although it can also facilitate incremental innovation (one example of innovation's cyclical nature). At higher production levels, the cost curve eventually flattens as the benefits from learning-by-doing diminish, as shown in Figure 3-9. The steepest cost reductions occur at the beginning of the process, particularly as the technologies proceed through the commercial demonstration ("commercialization") phase — although reductions continue during early commercial deployment. This is somewhat similar to what happens with ***economies of scale***, which also occur as the technology taxis towards market take-off — tempered by the observation that scale economies tend to peak later on, post-take-off. Sulfur dioxide scrubbers (aka flue-gas desulfurization, or FGD) installed on fossil fuel-fired electricity plants illustrate this effect. Driven by the Clean Air Act (U.S.), scrubbers have been installed on 179 GWe of (mostly) coal plants; over a 25-year study period, capital costs of scrubbers fell by nearly 50%.[86]

Figure 3-9: Cumulative production favors learning-by-doing, which in turn increases efficiencies and lowers costs



Although each of these cost-cutting methods is important, the most significant pre-take-off savings a rise from transformational R&D and learning-by-doing. The steepest cost reductions are available during the early output and commercialization phases, which means that prototyping and commercial demonstration projects play an outsized role in driving cost reductions. This strengthens the case for a more robust policy along this stretch of the S curve.

2. Faster Project Deployment

To address the twin challenges of replacing existing, CO_2-intensive sources at scale and meeting new energy demand, the take-off and diffusion of zero-carbon technologies must occur more rapidly than has historically been the case. For the past decade globally, thermal power construction times have hovered at around four years.[87]

One critical area plagued by delay is project development. This process can encompass everything from the creation of a range of prototypes, any number of demonstration projects, and numerous iterations along the road from FOAK to NOAK. Here, we look at the general issue, focusing on full-scale construction of complex plants. We conclude that the entire process can move faster — from the commencement of pre-construction activities, through construction itself, to commercial operation.[88] Cycle time between projects also can shrink.

Pre-Construction Time

Before construction begins, an energy project must be designed, permitted, and financed. In the U.S., this means obtaining commitments for all debt and equity investment. To get there, the design must be nearly complete and construction contracts signed. All government approvals, including environmental permits, must be in hand, as well as those of economic regulators, such as state-level public service commissions. Grants, loans, or loan guarantees from federal or state agencies may be required, and contracts to sell electricity or other energy-related products to credit-worthy entities must be final. The time needed to conclude this process generally is influenced by a given jurisdiction's regulatory policies and property rights regime, as well as project complexity.

Innovation policies can help to cut pre-construction time in several ways. For example, regulatory action can encourage standardization of key processes and inputs for a single project, and can facilitate the simultaneous or staged development of many similar projects.

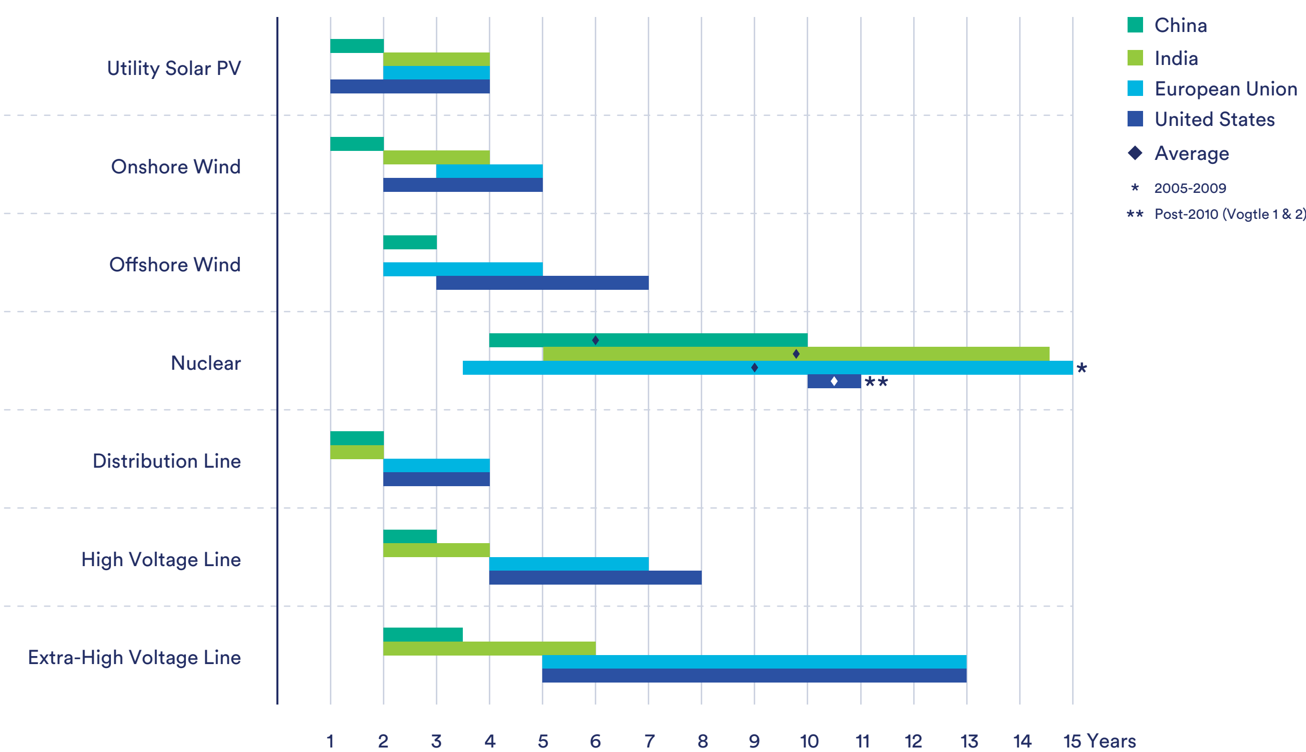
Incentives are also important. Ensuring that these are "self-activating" — that is, based on clear, pre-existing criteria that do not require before-the-fact, case-by-case agency approval — increases certainty that expected support will arrive; this, in turn, reduces cycle time. For policies requiring a *priori* approval, such as grants, contracts for difference,[89] or feed-in tariffs, more efficient regulatory machinery will also lower investment barriers and speed pre-construction.

Construction Time

The time required to get innovative technology into the ground is generally the most consequential metric for the global energy market. Construction time is primarily affected by the degree to which an innovative technology project is "stick-built" (i.e., with substantial engineering and construction on site) versus "manufactured" (i.e., with most components modular and manufactured in advance, then assembled on-site).[90] Historically, nuclear reactors have been stick-built, while major components of combustion turbines, wind generators, and photovoltaic panels are modular and manufactured in factories. Table 3-3 below[91] provides a range of construction time estimates for the major power generation and transmission technologies.

The greater the standardization and factory production, the more rapidly new energy technologies will be deployed. Partly through enormous project volume, China has demonstrated standardization's power. There, a coal plant can be built in a year, while in OECD nations the process typically takes five.[92] A reference plant approach, which uses standardized engineering design plans that have been only slightly modified for local conditions, can significantly reduce engineering costs and accelerate construction times — particularly when supported by strong supply chains and skilled labor. This strategy is employed extensively in the chemical industry and was a feature of the Canadian nuclear reactor (CANDU) program.

Table 3-3: Estimated construction time (in years) for electricity generation projects in China, India, the EU, and the U.S.



Another approach, especially useful for technologies that do not require intricate "industrial complex-level" work at individual locations, is to increase the fraction of zero-carbon product that is standardized and manufactured off site. As is clear with solar PV and wind power, the industrial engineering systems inherent in factory production drive down cost, unwanted variation, and risk. Standardized manufacturing also minimizes labor cost overruns, weather delays, and other scheduling challenges that cause construction expense to balloon. For example, GE fabricates small "packaged" natural gas combined-cycle plants in factories, then ships or flies them to their operating sites. A similar approach could be adopted for nuclear reactors — when sited, for example, at underutilized shipyards and delivered via sea. Combining the principle of standardization with the impact of learning-by-doing, one observer has noted that "a venture based on modular replicability is more likely to succeed than one that depends on long-range planning and forecasting."[93] Conversely, when a technology is complex and custom designed, the opposite can happen — what's known as "negative learning."[94]

Other advanced design and construction practices that will help promote standardization and cut costs include:

- Designing to a target budget;
- Drawing on open architecture for standardized competitive components, where possible;
- Using standardized scopes of work; and
- Taking advantage of advanced site fabrication technologies (e.g., 3-D printing).

Finally, and perhaps counter-intuitively, it makes sense to conduct robust engineering studies prior to construction. Although engineering analysis will later become more standardized, during development, it is important not to cut corners — particularly in the prototype and commercial demonstration phases.

Cycle Time

The time between projects, cycle time, is also a key temporal factor, particularly during the commercial demonstration phase. New technologies can be slowed by conservative investors' need to review results from one demonstration before agreeing to underwrite the next. But if a number of demonstration projects are required — and, for complex installations, they typically are — the period from final demonstration (Nth) project to take-off could end up being decades.

The Innovation Technology Framework can help to address this problem by aggregating commercial demonstrations of a given technology. For example, multiple technology vendors and their customers could be encouraged to develop a joint request for proposals (RFP). The process would be structured to deliver staggered demonstrations — from first-of-kind (FOAK) to projected Nth-of-a-kind (NOAK) — able to get underway quickly and in tight sequence.

3. Easier Access to Financing

Some $2 trillion is invested in the global energy sector annually. Investors at this scale include pension funds, retirement account trustees, insurance companies, and sovereign wealth funds. These entities are conservative both in practice and by regulation. Bending a substantial investment stream toward zero-carbon energy technologies requires that both the technologies and project deal structures be viewed as secure and prudent in the eyes of these largest, most risk-averse pools of capital.

To attract institutional investors, technologies must be deemed "proven and tested." This means that they have been successfully replicated over a number of units, preferably at or near commercial scale. At minimum, they must have reached the NOAK stage or offer standardized design and display solid technological performance. As projects begin to deploy beyond the Nth plant, the structure of financial support (e.g., the relative amounts of debt and equity, sources of financing, and rates of return) becomes more transparent, reducing perceived investor risk.

Table 3-4 below matches levels of investor comfort to technological maturity. Over the past few decades, solar PV and wind projects have proceeded beyond NOAK to full deployment. This means that the technology and accompanying deal structures are viewed as totally de-risked. As a result, financing has become relatively easy to obtain, particularly given promised returns. Conversely, given the current rarity of large new nuclear projects and the absence of advanced fission technologies, nuclear energy is deemed "immature" — that is, an old technology, with question marks around both deal structure and performance.

When it comes to low-cost financing, the Innovation Technology Framework's primary value is in expediting and regularizing the development of demonstration projects. But, as the experience with PV and wind

Table 3-4: The ladder of clean energy investment

Stage of Financing		Debt and Equity Market Acceptance	Zero-Carbon Technology Status
Immature	D	Government loans, loans from Export Credit Agencies (ECAs) related to foreign manufacturer, big company balance sheet borrowing	Wind and Solar PV: Reached this level in 2005 Nuclear: Recent projects reached this level in 2010. Examples of 1000 MW+ plants include Vogtle and Emirates Nuclear[a] CCS: Reached this level in the power sector in 2010. Petra Nova is an example
	E	Developers, regulated utilities w/PUC approval, manufacturers	
Aggressive Lenders and Equity	D	Plus some banks will do a combination of guaranteed (gov't or ECA) and unguaranteed project finance loans	Wind and Solar PV reached this level between 2008 and 2010
	E	Plus some very aggressive private equity firms specializing in energy	
Wider Acceptance	D	Plus experienced banks will make project finance loans at fairly high rates	Wind and Solar PV reached this level between 2010 and 2011
	E	Plus wider acceptance by variety of project equity funds, direct investment by climate-friendly wealthy companies[b]	
Fully Mature	D	Investment grade ratings available, giving access to long-term bonds; banks forced to compete aggressively for business	Wind and Solar PV reached this level in 2011. Examples include Topaz, Solar Star[c]
	E	Direct investment by aggressive, well-resourced pension funds. Formation of publicly traded equity vehicles such as "Yieldcos" to give retail investors access	

[a] *Emirates Nuclear is $18.95B in loans: 86% from Abu Dhabi sovereign; 13%, Korea Eximbank; 1%, commercial banks.*

[b] *Google's investment in Alta Wind appears to be its first direct investment in wind or PV.*

[c] *The first major investment-grade renewable deals hit the market in 2012, with the two mentioned here under Berkshire Hathaway.*

has shown, it is not enough to support a new, clean technology to the point of take-off, and then stop. During the initial years of market diffusion, new clean technologies require continued support, just at a different level and of a different kind. That is where incentives like production tax credits (PTCs) can be most effective. In the U.S., the wind PTC and the solar investment tax credit (ITC) have been essential in moving these technologies well up the S curve.[95]

One further note is that venture capital (VC) also can play a role, but generally at an earlier stage of technology development. VC investors back risky new technologies in exchange for an ownership stake, implicitly acknowledging that much of their portfolio will not pan out. Although venture capital funding of clean energy technology has varied a great deal historically,[96] current evidence suggests that VC support can be important during R&D, helping promising start-ups to bridge at least the first valley of death.[97] Nonetheless, venture capitalists generally seek returns of 10-100 times their initial investment, while anticipating payoff in only three to five years.[98] These expectations may fit certain new energy technologies, but clearly not long-range possibilities facing decades of research and development.

4. Overcoming Ecosystem Barriers

Zero-carbon technologies must have the capacity to address problematic structural constraints. These so-called "ecosystem barriers" may include elements that are not directly related to a given zero-carbon technology itself or its market price, but that nevertheless could hinder that technology from reaching market maturity.

The concept of an "innovation ecosystem" is highlighted in a recent *Harvard Business Review* article by Ron Adner and Rahul Kapoor, scholars of entrepreneurship and management at the Tuck School of Business at Dartmouth College and at the University of Pennsylvania's Wharton School, respectively.[99] Observing that some technologies immediately surpass the existing competition, while others take decades to do so, Adner and Kapoor looked beyond price and market operation to examine the degree to which a new technology is affected by the external state of play — in particular, innovations in complementary technologies, services, standards, and regulations. They call this an innovation's "ecosystem," and are particularly interested in the relationship and the degree of overlap between the ecosystem in which an existing technology operates and the ecosystem that a new, rival technology needs.

Adner and Kapoor observe that a new technology substitutes for an existing technology most rapidly when the new technology fits tightly into the ecosystem of the old — an example would be portable printers, where inkjets were able to quickly overcome the dot-matrix incumbent because both relied on the same cables to connect to a computer.

Conversely, the slowest substitution occurs when the existing technology can be further upgraded, while the new one requires significant ecosystem alteration. An example is the relatively gradual replacement of gasoline-powered cars with electric vehicles (EVs). Here, the particular circle of concern extends beyond the consumer products themselves (cars) to the broader systems in which they are used and in which they must compete. For EVs, that system includes the charging infrastructure, the absence of which poses a significant barrier; for gasoline-powered vehicles, the challenge is more internal to the vehicle itself and its existing support structure: how to extend useful life through additional fuel efficiency or other incremental improvements.

The authors broadly identify four key junctures at which the S curves of an existing and new technology can interact — with differing results depending on the structure of their surroundings. This typology offers an additional filter that can be applied to help locate the point at which efforts to reduce cost, accelerate deployment, and ensure strong financial backing will be most successful. The following is an interpretive summary of their framework:

Case 1: *Rapid Replacement:* New technology substitutes most readily in this quadrant because it uses the same ecosystem as the old technology, and the old technology has exhausted its potential for improvement. Examples: 3 MW wind turbines replacing 500 kW turbines; halogen and LED lighting replacing incandescent and compact fluorescent bulbs; ink-jet printers replacing dot-matrix printers.[100]

Case 2: *Extended Co-Existence:* Substitution is gradual and occurs later. Here, the new technology fits into the old technology's ecosystem, but the old technology can still be significantly improved. Thus, the new technology must achieve a higher level of performance before it is able to dominate. Example: Hybrid engines replacing internal-combustion engines; flash drives vs. hard drives.

Case 3: *Status Quo, then Rapid Replacement:* Here, substitution occurs later, but then moves quickly. The new technology's ecosystem is not fully developed, but the incumbent technology has little room for improvement. In this quadrant, the new technology faces fewer obstacles in supplanting the old. Examples: GPS navigators replacing paper maps; high-definition television replacing standard TV.

Case 4: *Incremental Replacement:* Existing technology retains its hold longest where the new technology's ecosystem is not well developed and the incumbent can take advantage of multiple improvement opportunities. Compared with the other three scenarios, the new technology will require the highest level of improvement relative to the old. Example: EVs replacing gasoline-powered cars.[101]

The above typology provides a helpful guide for identifying the S curves most likely to achieve greater height and compression. But, to apply it to climate technology, a broader circle of ecosystem constraints must be considered, particularly those that encompass public policy.[102] These include the existing legal and regulatory framework, international agreements and informal cooperative customs (or their absence), the tenor of the political arena, and even public perception (see Box: Classifying the Types of Barriers). This broader scope is even more imperative in the energy sector, which is riddled with market imperfections.[103]

Classifying the Types of Barriers

Given that their removal animates one of the four levers of success, it is important to identify and prioritize the key ecosystem barriers that confront a given energy technology innovation. Those barriers range from an unfriendly political or regulatory environment, to the physical absence of key support structures or technologies. And they can vary widely among technologies, industries, and development stages. In fact, they tend to be both complex and specific to particular innovations, meaning that there can be no substitute for individualized examination. Still, it is helpful to begin with a general typology — a list of categories and common hurdles, along with examples of technologies where such barriers are especially problematic:

Table 3-5: Ecosystem barriers in the energy sector — examples

General Area of Barrier	Type of Ecosystem Barrier	Brief Example(s)
Political	Adverse public perception	Central-station nuclear
	Lack of legislative knowledge	Fusion
	Politicized legislative or executive perception	Vehicle mileage standards; biofuels
Legal	Community-based zoning and land-use laws	Wind and solar power
	Federal Clean Air Act	Trading of CO_2 emissions from multiple sources
	Federal Clean Air Act	Extension of California primacy to hydrogen-fueled automobiles
Regulatory	Outdated licensing requirements	Modular nuclear reactors
	Uncoordinated licensing regimes	Carbon capture, transportation, and sequestration
Industrial	Existing actors opposed to change	"War on coal"; utility opposition to net metering for PV
	Lack of coordination between existing and new technologies	Installation of CCS on power plants
Financial	Match with investor expectations re: rate of return	Superhot rock geothermal energy
	Uncoordinated financial signals	CCS
Conceptual	Political belief that S curve progression should be driven solely by private markets	Wind and solar energy; CCS; nuclear; superhot rock geothermal; energy efficiency; EVs (to name a few)
	Negative externalities ignored	Same as above

Some barriers appear only after a given innovation reaches a specific threshold or achieves particular regulatory support. The existing electricity grid, for instance, is able to remain relatively stable while handling current levels of wind power and solar PV. But, as these variable renewables continue to expand, the situation is likely to change — with wind and solar forced to operate inefficiently (that is, at less-than-achievable capacity) or with the energy system required to invest in expensive new ecosystem components — for example, major new transmission lines and long-duration power storage. A second example: the relative desirability of coal- vs. gas-fired electricity generation may be altered if upstream greenhouse gases are accounted for. Or: a given technological approach may require a stable integration point (e.g., where an active electric car market meets a single, established charging standard), providing a more-than-momentary plateau that anchors confidence in consumers and investors.

The need to consider the broader support structure (that is, the wider ecosystem) is particularly evident for technologies featuring large, complex operations that accommodate lower levels of modularity. For example, a successful carbon-capture and sequestration (CCS)[104] facility requires major, integrated infrastructure — particularly carbon dioxide pipelines and geologic sequestration sites. In addition, this technology would benefit from a more integrated permitting process. CCS ecosystem needs also encompass expertise in CO_2 capture, transport, injection, and subsurface management. For nuclear energy, adequate national regulatory regimes within international governance are major missing elements; another is the absence of supply chains and construction infrastructure, which have been lost as associated industries, facilities, and technical expertise has dwindled or deteriorated; and a final wild card is public support, or at least the absence of grinding opposition.

This analytic process also will need to take into account particular physical constraints — either systemic or arising from a specific crisis. These include supply chain bottlenecks, fewer skilled workers, and limits to the private sector's ability to handle a surge in technology transactions.

No universal prescription exists to address the structural constraints facing zero-carbon technology. Surmounting these will require approaches suited to each technology in its present stage of development. Early on, innovations may benefit from targeted infrastructure policies offering grants and loans. Later, the support of national or sub-national infrastructure planning authorities may be called for. Permitting pathways will need to be developed throughout, from the first demonstration project to market maturity.

Finally, and of critical importance, international structural constraints and challenges must be taken into account — particularly the needs and vulnerabilities of developing nations. Many of these economies have not yet built an electricity grid or a fuel pipeline system able to support significant commercial growth. In some, the negative impacts of existing infrastructure disproportionately affect the least politically powerful.

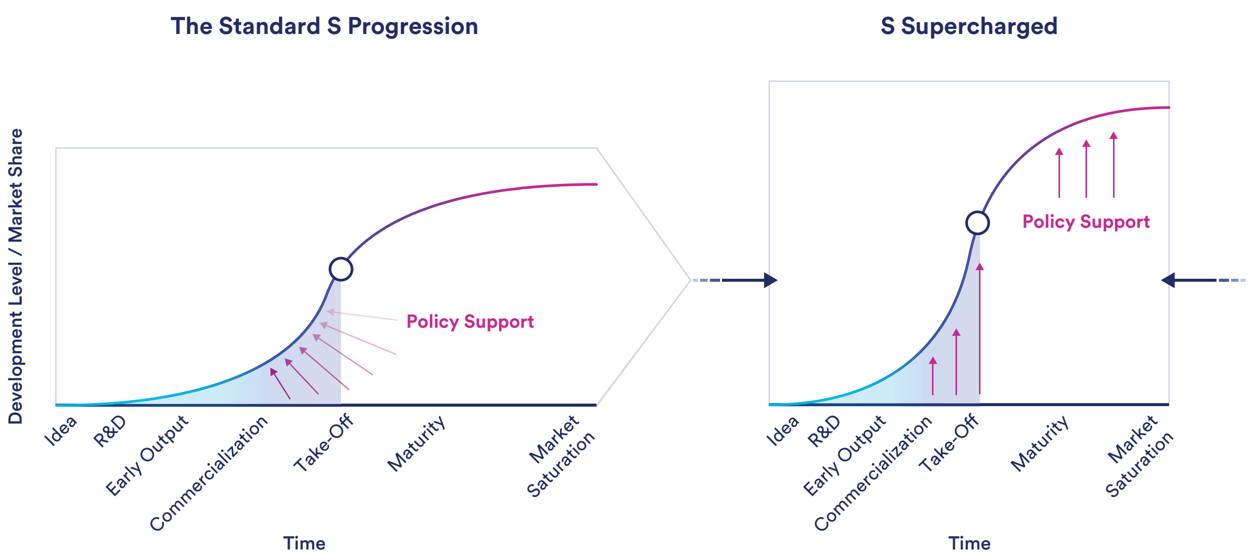
In addition to expressly including equity as a structural requirement (and thus an ecosystem element), we also must consider how energy research, as well as later steps in the innovation process, will be conducted across continents and among entities — corporations, for example — whose power extends beyond national borders. Some have suggested that, absent a broad, effective international coalition, developed countries should prioritize collaboration around specific technologies within their structural ecosystems. Although this may not be ideal from an equity standpoint, it could serve as a more reliable and efficient way to meet the mounting threat of climate destabilization — and success there will especially benefit some of the least prosperous communities on Earth.

E. Further Examples of the Innovation Framework in Practice

1. Introduction

The key ingredients linking the initial development stages of energy innovation and its major levers of success are policies that have been carefully applied to the correct stages of the S curve. Although policy support should exist along the entire curve, even after take-off, its intensity will vary, depending on the stage. This is shown graphically below in Figure 3-10.

Figure 3-10: Focused policy mechanisms compress and deepen the S



Connecting the Innovation Framework to Other Policy Concepts

As the main text makes clear, we need a far more intentional innovation technology system — not the ad hoc contraption that exists today. To get there, we'll have to focus on the institutional and policy interventions most likely to work, and to coordinate the timing of their appearance. These often are referred to as "demand-pull" and "supply-push" strategies. But an effective innovation framework directs these strategies in more precise ways – and, crucially, integrates them in ways that maximize their combined benefit. In the process, it gives policymakers a tool for thinking more concretely about how to apply these key policy drivers to real-world settings. Figure 3-11 below provides a graphic representation.

Demand-pull attempts to stimulate market demand for a given technology. Its repertoire includes well-understood carrots like tax credits that incentivize specific activities, as well as regulatory sticks, such as emissions-based performance standards, technology-based standards, technology mandates, cap-and-trade systems, carbon taxes, competitive auctions, and renewable portfolio standards. Others, such as the feed-in tariffs preferred by some members of the EU and production tax credits, possess qualities of both demand-pull and supply-push. Many observers of the innovation technology process are skeptical that demand pull mechanisms, standing alone, can effectively rein in carbon.[105]

Supply-push, conversely, aims to reduce the barriers described here by focusing more on the technology development process. Its techniques are mostly of the positive, carrot type, and can support all phases, from R&D to take-off. They include direct funding, grants, loans, loan guarantees, competitions, education and training, and production tax credits. Some recent analyses suggest that demand-pull policies are better suited to mature technologies, while supply-push policies are the top choice for emerging innovation.[106]

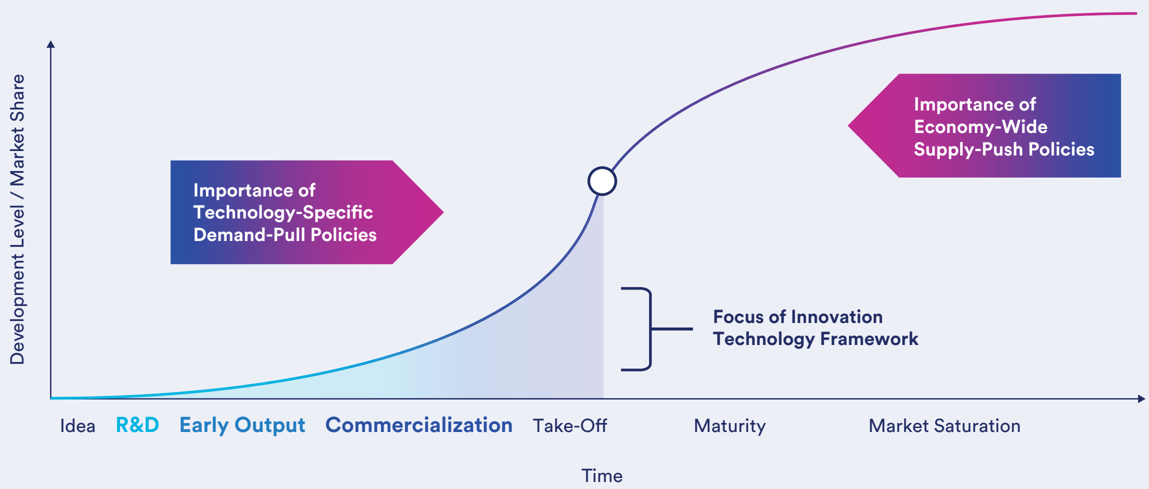
These two policy drivers differ in important ways. Demand-pull (particularly when operating in the regulatory background) often tends to influence the entire innovation technology process. A carbon tax, for instance, will affect everything from the initial invention to the structure of the final market. And its impact is quite general. Conversely, the impacts of supply-push, generally most effective during the R&D, demonstration, and ramp-up stages, are narrower — focusing on a particular stage, actor, project, or technology.[107] Nonetheless, optimal results may be achieved when the two drivers work in concert – for example, to develop modular nuclear reactors in the U.S., by combining research, development and demonstration funding under the 2022 Inflation Reduction Act with new EPA regulations under sec. 111 of the Clean Air Act to limit carbon emissions from fossil fuel-fired power plants.

The Innovation Technology Framework builds on these concepts in significant ways. It clarifies when, where, and how to structure these strategies to achieve maximum effectiveness. Consider how the framework helps to address these central objectives:

1. Tailoring demand-pull policies to a specific technology's position in the S curve

As noted above, some demand-pull policies affect the entire S curve. New legal mechanisms like carbon taxes or new forms of emissions limitation requirements that include cap-and- trade systems can be designed to apply across the economy. However, some potentially major technologies (e.g., superhot rock geothermal) aren't yet mature enough to respond to these broad measures. They require demand-pull policies tailored to their situation, and these tailored policies must be in place long enough to allow the technology to reach take-off. The lens of the innovation framework clarifies the importance of the first part of the S curve, allowing for a more precise policy response.

Figure 3-11: The forces of expedition — disaggregated



2. *Tailoring supply-push policies to the appropriate stage and technology*

The innovation framework can also help to clarify when supply-push policies work. As noted earlier, these include grants, loans, and tax credits. Project sponsors must apply directly to a government agency to qualify for many of these programs. This process is appropriate in the R&D and early commercial stages: there, projects are more risky and diverse, requiring the customized attention of funding agencies and reviewers.

However, at the commercialization stage, the goal is to build many projects in a short period of time. This increased scale calls for a different approval mechanism. Developers must be able to avail themselves of self-activating policies – ones that do not demand advance government authorization. For example, in the U.S., a developer can claim wind and solar production tax credits (PTCs) solely by reporting output levels that meet published PTC requirements. The 45Q tax credits that support CCS are also performance-based; a developer receives them based on documentation showing how much CO_2 has been isolated from the atmosphere.

3. *Identifying what policies will work best*

Perhaps the most significant benefit of the Innovation Technology Framework is that it allows both demand-pull and supply-push approaches to be coordinated, individually or in tandem, with the four levers of success —

- Lower costs;
- Faster project development and deployment;
- Easier access to financing; and
- Removal of ecosystem barriers —

so that these varied policy approaches can be more precisely tailored to the points at which a given technology is likely to stall. Not every technology needs support in each of these areas. As shown in the following section, the innovation framework can help to channel resources to their most effective place on the S curve.

2. Applying the Framework: Examples

Below we examine three varied technology challenges through the lens of the innovation framework to better identify the specific policies that will be of greatest benefit, given a technology's location on the S curve.

Hydrogen Stations for Heavy Trucking in the U.S.

An example from transportation involves plans to convert heavy trucking to decarbonized hydrogen fuel. The first step in using the innovation framework is to locate the challenge on the S curve.

These trucks are being tested in California around the Port of Los Angeles and will soon be at ports in the Bay Area — drawing on the local hydrogen infrastructure. Currently, just under 50 light-duty public hydrogen stations exist in the U.S., nearly all of which are in California. The demonstration involves heavy trucks powered by two passenger-vehicle fuel cells or by a fuel cell and a battery. Although viable, the technology needed to haul 80,000 pounds of cargo up hills has not yet matured to the level now seen in passenger cars. Thus, heavy trucks fueled by hydrogen are at the early output or the beginning of the commercialization stage.

The second step in using the innovation framework is identifying which of the success levers are most important to focus on. The challenges facing heavy trucks invoke at least two of them. First is lowering costs. The price tag for heavy-duty diesel trucks is between \$100,000 and \$200,000, while fuel cell versions can run upwards of \$1 million (battery-powered heavy trucks are \$600,000 to \$800,000). Hydrogen is also a very expensive fuel at present. Currently in California, at more than \$18 for the equivalent per-gallon of energy, it costs three times more than diesel. This is a significant hurdle, especially for freight businesses, which typically survive on small margins. A second key lever focuses on overcoming ecosystem barriers. Before testing a major cross-country route, a chain of hydrogen refueling stations will be required.

The last step in the innovation framework is to identify what's needed: a suite of policy measures to pull hydrogen trucking across the third valley of death[108] and ultimately compress the S curve. Fuel production costs can be offset with direct policies like a federal production tax credit, or direct subsidies to station operators or fleet owners. Indirect policies — e.g., scaling up nationwide hydrogen capacity via production hubs — also will help. Grant programs can lower truck and station capital costs, and also speed development of zero-emission trucking corridors. And states can drive the action, particularly if more jurisdictions adopt blanket policies like California's Low Carbon Fuel Standard (LCFS) and its Advanced Clean Trucks (ACT) rule.

Ultimately, the growth of hydrogen will need to be channeled via both demand-pull and supply-push mechanisms. The former includes the existing California ACT rule, which operates as a zero-carbon mandate for trucks;[109] the latter might involve funding or partial tax credits to build hydrogen hubs, and adoption of a low-carbon (or, preferably, a zero-carbon) fuel standard — ideally at the federal level.

All of these public actions are spurring automakers to get involved. For example, a public-private consortium in California is working to increase the number of hydrogen fueling stations, while an EV manufacturer has teamed up with a renewable fuels provider to develop a national chain of hydrogen stations for heavy freight haulers.

Bringing NH_3 fuel into the Mix for Marine Shipping

A second example, also from the transportation area, involves part of a larger system aimed at decarbonizing the international shipping industry. Here, the goal is to phase in ammonia fuel using dual-fuel engines, reducing carbon dioxide emissions from marine vessels.

In terms of the S curve, this process remains at the R&D phase. But this is less the result of technical feasibility than a variety of organizational, regulatory, and economic challenges — in other words, a cluster of structural or ecosystem barriers, including fuel availability and safety precautions. There also is a less-central, but still important concern about price — which brings to bear the first lever of success (lower costs).

Marine engines will soon be available that can operate on a combination of ammonia and conventional heavy fuel oil. The limiting factor will be fuel storage capacity. Due to ammonia's lower energy density, three times the on-board storage tank capacity is required to fully fuel a ship with ammonia. Availability of low-carbon NH_3, made with natural gas backed by carbon capture or with zero-emission electricity from renewable or nuclear energy will be a key factor in when and how fast the marine sector invests in on-board ammonia fuel capacity. Others question this approach; they prefer transitioning to biofuels, rather than weaning off marine fuel oil via ammonia. Either way, the remaining ecosystem obstacles are relatively modest. They include the lack of onboard vessel safety standards (ammonia is toxic) and inadequate port infrastructure. Some additional infrastructure is needed, such as ammonia bunkering at ports. But this is not a deal breaker, given that the number of major ports is relatively small. As noted, money also is of concern, as “bottom-of-the-barrel” heavy fuel oil currently is the power source of choice. Ammonia, while less costly than hydrogen, is more expensive than this dirtiest of transportation fuels.

Although fuel-blending remains at the R&D level, it is important to note that there already exists a mature industry that produces and transports ammonia, much of it by ship. Because ammonia is created by combining hydrogen and airborne nitrogen, the commercial resource is likely only to increase, as more hydrogen — produced by green technologies such as methane reformation backed by carbon capture, or electrolysis powered by clean energy — becomes available. At a broader level, several European companies are leading the way in developing vessel engines able to accept a higher percentage of ammonia. In fact, at least one shipping firm has entered into a memorandum of understanding to purchase one or more duel-fuel vessels able to burn pure ammonia.[110]

What solutions does the innovation framework suggest? Given the global nature of shipping, the policy issues can be complex. The International Maritime Organization (IMO), a specialized U.N. agency whose membership includes nearly every nation, recently updated its climate policy for the global marine sector to reach net-zero by “around 2050.”[111] The agency has initiated a two-year process to develop a global fuel standard and economic measures to meet this goal, which will shorten the S-curve and expedite change.

The bottom line: for ammonia blending and repowering on the high seas, the primary barrier is not chemistry, but politics. Right now, it is not the lack of policy mechanisms of the supply-push and demand-pull variety; rather, it is the need to further develop an institutional platform from which to design and apply those policies.

Advanced Nuclear Requires a Versatile Test Reactor

The versatile test reactor (VTR) would be a single, government-overseen test facility able to perform large-scale, fast-neutron irradiation experiments focusing on the fuels, materials, and sensors required by key advanced reactor technologies.[112] In addition to helping reclaim U.S. prominence in nuclear engineering, the VTR program is essential to scientists' understanding of what does and doesn't work in the extreme internal environment of advanced reactors. These include sodium-cooled fast reactors, viewed as one of nuclear energy's most promising future technologies, as well as related advanced reactor designs. Right now, the entire fast reactor program is at the research end of the R&D phase on the S curve, but the versatile test reactor itself is proceeding through U.S. DOE's approval process. Even though the test reactor has surmounted just the first of the agency's four critical design steps, no major technical snags are projected, given that the VTR is based on existing designs and that DOE already has experience operating fast reactors.[113]

The versatile test reactor would also enhance implementation of the recently-passed Inflation Reduction Act of 2022 (IRA). And the IRA's generous tax credits could up the odds for advanced reactor deployment in the near term — and thus the potential for decarbonizing the energy sector. However, the U.S. Nuclear Regulatory Commission will need data from VTR tests in order to license many of the advanced reactor designs currently on the horizon. This testing capability will also be crucial in helping to reduce the capital, operating, and lifecycle costs of fast reactors.

The VTR has been authorized at DOE's Idaho National Laboratory, but not yet funded.[114] And that points to the key success lever that is now the sticking point — the need for Congressional appropriation of at least $750 million for each of four fiscal years. Alternatively, it might be better if the VTR were supported by an entirely new funding model — one that doesn't depend on Congressional approval. Either way, the need is great. Ultimately, the VTR is central to the long-term success of sodium-cooled and other fast reactors. Right now, the path prescribed by the innovation framework is clear: funding is top priority.

3. Summary

The following table briefly summarizes the status of many of the major technologies that will or are likely to be called into service as part of the global response to climate destabilization. It applies steps (iii) through (v) — the core of the five-step process outlined at the beginning of this sub-section — to those technologies: that is, where the technology now sits on the S curve, what success levers are key to compressing and deepening the curve, and what policy measures are most likely to do that. As is clear, wide variation now exists among levels of technological development. To help ensure a robust climate response, this will need to be addressed.

Table 3-6: Where the major zero-carbon energy innovation technologies stand and what they face

Advanced Zero-Carbon Technology	Current S Curve Position	Key Levers of Success	Potential Public Policy and Private-Sector Actions Needed
Wind	At/beyond take-off	Removing structural barriers; faster deployment; access to financing	• Offshore wind financing • Land-use regulation relaxation • Funding of seasonal storage R&D • New long-distance transmission lines
Solar PV	Near/at take-off	Removing structural barriers; faster deployment	• Land-use regulation relaxation • Funding of seasonal storage R&D • New long-distance transmission lines • Integration with regulated utilities
Long-term battery storage	R&D	Funding; access to financing; removal of structural barriers	• Integration with regional power pools
Hydrogen fuel for transportation	R&D	Removal of structural barriers; funding	• New trucking and shipping regulations • Safety regulations • Inter-jurisdictional coordination • Coordinated industrial policy
Advanced nuclear (fission)	R&D, with some demos	Removal of structural barriers; funding	• Licensing reform • Public education
Advanced nuclear (fusion)	Early R&D	Funding	• Development of licensing regime • Public education
Superhot rock geothermal	Early R&D	Funding	• Link to existing geothermal programs • International cooperation • Site identification
Carbon management: carbon capture and storage (CCS)	Demonstration, beyond FOAK	Removal of structural barriers; funding; access to financing	• Regulation to promote hub and spoke systems • Long-term storage regulations • Storage site identification • Stronger limits on carbon emissions
Carbon management: direct air capture (DAC)	R&D	Funding	• Investment in use of captured carbon

SECTION 4

Deploying the Energy Innovation Framework

A. Introduction

Climate-forward innovation policy must deliver decarbonization technology options that avert the main risks posed by chronic climate disruption. The Innovation Technology Framework described in this Report serves as a platform for optimizing institutions, policies, and strategies that bring more and better zero-carbon technologies — real-world options — to scale on time. In an optimizing environment, this work is collaborative and iterative. It incorporates feedback from other stages of similar initiatives, unrelated but potentially useful research, and institutional linkages that speed the process and render it more effective. And, at least initially, an effort like this must take pains to coordinate with existing entities — from legislatures and international agencies, to research universities and foundations.[115]

Still, innovative energy technology can stumble at many points along the way, not the least of which are the several "valleys of death." And the end can come even after multiple demonstration projects or initial deployment shows that the technology works at scale. A unified Innovation Technology Framework helps to avoid this fate. It can generate integrated strategies that optimize success, while working to analyze (and learn from) failure. Fundamentally, the zero-carbon innovation framework is a continuous, recursive, and evolving set of policies and institutional actions grounded in reality, not an abstract academic exercise consigned to specialized research journals.

This final section considers the broader picture of what a comprehensive innovation framework requires. Figures 4-1 and 4-2 offer a preview. Figure 4-1 shows how selected policy mechanisms follow similar but not identical S curves. Note that some may develop as a result of input from other technologies (S curves) and each may move at a different rate (thus, the x-axis is merely ordinal). Figure 4-2 looks at one specific S curve and locates it among the clusters of applicable policy mechanisms, which apply to one or more stages in the development of each technology. As the concluding discussion below makes clear, optimizing these energy technology innovations means that they must remain connected under the broader umbrella of the Innovation Technology Framework: integrated policy mechanisms backed by coordinated government and private action.

Figure 4-1: Schematic view of innovation (S) curves for various energy technologies, comparing them by phase of development (but not by timing)

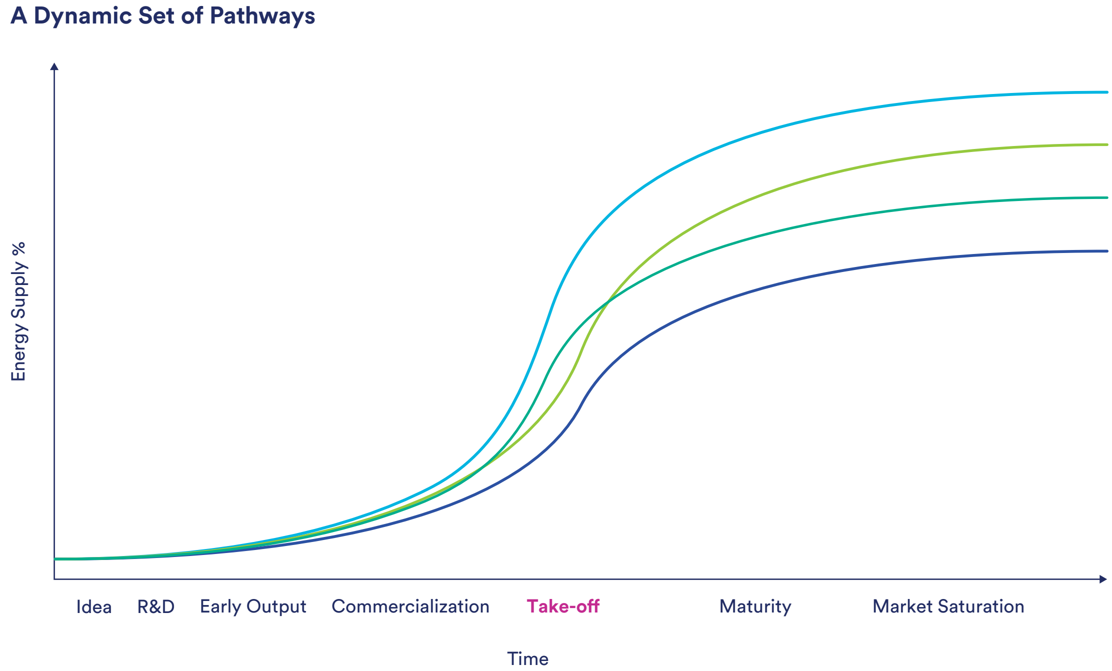
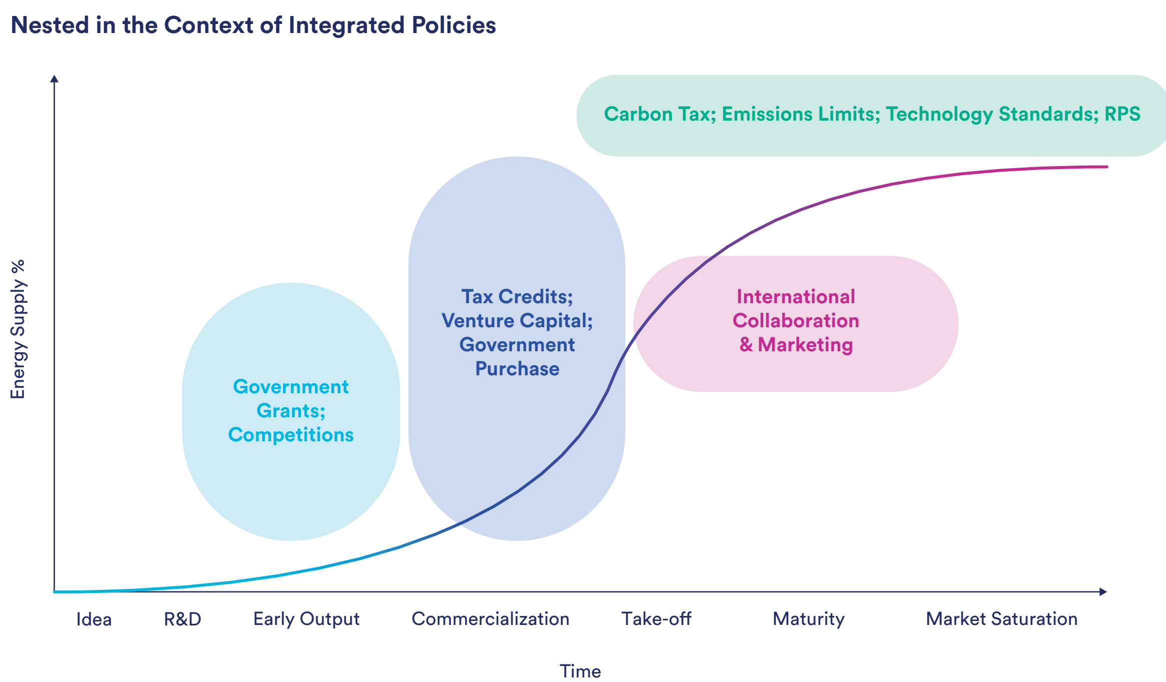


Figure 4-2: Relationship between an innovation (S) curve and relevant policies

Note that policies are tailored to the development level of a given energy technology.



B. The Overarching Propositions

A more general set of propositions to guide energy innovation policy emerges from the innovation framework detailed in the preceding sections. Each of these represents a broader goal that, if pursued, increases the probability that new, consequential energy resources will be available in time to address climate destabilization.

This Report is the product of extensive conversation of a core team of energy experts who represent diverse backgrounds and disciplines. Its members are listed in Appendix A. The ten propositions below distill the thinking of this group, as refined and filtered through the first three sections of this document:

1. The pool of options must be expanded.
2. From the start, innovation should aim toward its end goal: market take-off.
3. The most challenging steps ought to remain the focus.
4. Policy tools should fit both the technology and its address on the S curve.
5. Public/governmental financial support is essential until a technology achieves take-off.
6. Policy mechanisms must be simple, clear, and, at the commercialization stage, self-executing.
7. Public communication should clearly differentiate between the demonstration stage and the FOAK-to-NOAK progression — with narrative built from on-the-ground examples of learning-by-doing.
8. Success requires that key ecosystem barriers be identified and addressed.
9. Nationally, this transition will require business, finance, and government to apply industrial policy to innovation technology.
10. Internationally, innovation policy requires integrated leadership from those nations, multinational institutions, and global corporations best positioned to move energy technologies forward.

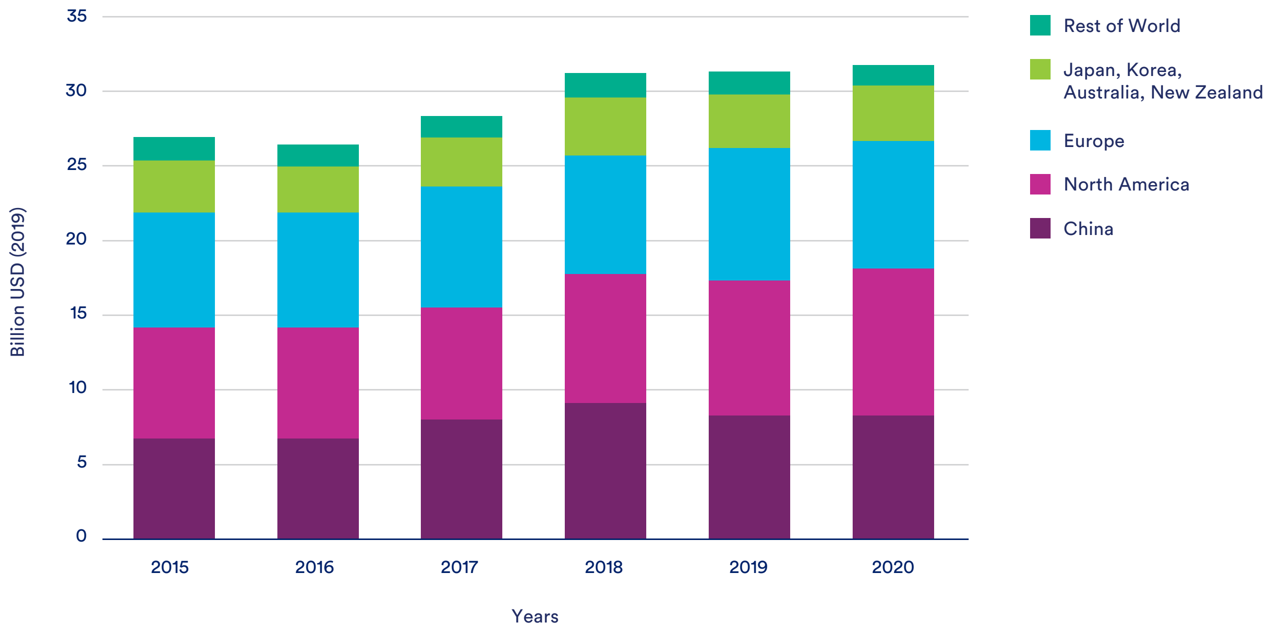
1. The Pool of Options Must Be Expanded

A zero-carbon Innovation Technology Framework must encompass and integrate an expanded range of scalable energy resources. Innovation is not a one-off process; it is a continuous evolution of new ideas, advanced by trial and error. As noted, not all ideas make it to market; many, in fact, do not (and some should not).

This highlights the importance of steady support for concept creation. This is the entry point to R&D, ensuring a continued flow of new ideas and approaches — some to overhaul existing processes and others to revolutionize the entire energy system. Two important implications follow: (i) R&D funding must expand; and (ii) the methods through which governments support R&D should continually be reviewed and improved.

Globally, public investment in energy R&D has hovered at only 0.02% of GDP in recent years. Although investment rose by 10 percent from 2021-2022, nearly all of that came from China (see Fig. 4-3 below).[116] Given the threat of climate change and the scale of the zero-carbon transition, R&D funding should increase to that of other major government initiatives. In the U.S., the Institute for Technology and Innovation Foundation (ITIF) has recommended that annual spending triple to $25 billion by 2025. That would place the U.S. on par with China in investing about 0.08% of GDP for energy research and development. OECD countries, which as a group are ahead of the U.S., should also increase their commitment.[117] Right now, a number of developed nations have issued national clean-energy strategies, including France, Japan, Norway, Finland, and Sweden, and are investing larger fractions of their GDP than the U.S.,[118] although new R&D funding under the U.S. Inflation Reduction Act should help narrow that gap over the next five years.

Figure 4-3: Government spending on energy R&D worldwide — except for China, stuck in low gear ever since Paris



In part, improved R&D means greater focus on transformative innovation rather than incremental innovation. A particularly interesting model for transformative R&D is the U.S. Department of Energy's energy incubator, formally known as the Advanced Research Projects Agency–Energy (ARPA-E). Authorized by Congress in 2007 and funded two years later, the agency was modelled on the successful Defense Advanced Research Projects Agency (DARPA).[119] In the area of innovation, ARPA-E's duties include the reduction of long-term market barriers, market failure, and risk.[120] In little more than a decade, ARPA-E has had significant commercial success in catalyzing public-private partnerships around innovation. Because its vetting processes are seen as highly rigorous, private sector investors give significant weight to its decisions.[121] Since 2009, over $2 billion in R&D support has led to the creation of more than 109 new companies, the approval of 253 licenses, the generation of over $7.6 billion in private-sector follow-on investment, the publication of 4,871 peer-reviewed journal articles, and the issuance of 789 U.S. patents.[122] In many ways, ARPA-E is a model of how a focused public agency situated on the periphery of the political torrent can organize technological development in a way that begins to resemble a comprehensive innovation framework — one built to support transformative, high-risk, high-reward technologies. And unlike venture capital, ARPA-E provides key seed money without diluting founders' equity.[123]

Improved R&D must include, but proceed beyond, approaches that primarily focus on current clean energy production (e.g., renewables, nuclear, and fossil fuel with carbon capture). It also must address how energy carriers like hydrogen can most effectively advance. Similarly, end-use options for electrification and zero-carbon fuels should be developed in a more systematic manner.

2. From the Start, Innovation Should Aim toward its End Goal: Market Take-Off

An specific innovation's beginnings ought to establish a clear link to the paramount objective: thriving zero-carbon technology markets across the globe. To increase the odds of success, technology R&D should consider manufacturing and construction cost and speed, scale of deployment, and ecosystem barriers (e.g., infrastructure challenges and licensing needs) — right from the start.[124]

For example, by considering manufacturing at the R&D stage, innovators can consider the use of open architecture to incorporate standardized competitive components. Likewise, construction practices should involve standardized scopes of work, as well as modular components and advanced site fabrication technologies (e.g., 3-D printing). This approach positions technologies to behave more like "products," in contrast to large-scale, one-off structures that are custom-built in the field (and that may never move from the "project" stage to the "product" stage). Finally, in some cases, it would help were R&D to pay less attention to the perfect and more to the good — that is, to what's feasible on the ground. This may involve designs that reconfigure existing materials and practices, rather than making everything "new."[125]

Moreover, cost objectives ought to be reinforced by advances in technology design that address speed and scale. For example, to facilitate 3-D modeling, the U.S. Department of Energy recently provided a $5.8 million grant to Hitachi to pilot standardized composite construction materials and advanced monitoring technologies. Another possibility: an open-architecture approach to nuclear reactor design could produce standardized components drawn from open-source intellectual property, allowing technology vendors to focus on design of the core nuclear unit. In fact, Transcorp Group, Nigeria's largest electricity producer, has expressed interest in procuring a reactor manufactured in this way.

R&D policy also can be structured around projected cost targets, particularly those based on transformational R&D. This can be illustrated via negative example, one involving DOE's SunShot program. SunShot was established in 2011 to reduce solar technology costs by 75% and to do so in less than a decade. In 2017, DOE certified that, for utility-scale solar, this goal had been met — three years early. So that same year the agency announced a new goal: another 50% reduction in solar costs by 2030. Unfortunately, much of the 2011-2017 price plunge was due to new demand triggered by U.S. and EU deployment policies, combined with China's massive scale-up of conventional silicon-based PV production.[126] It was not because of innovation. An alternative program might have helped industry address emerging commercial challenges, such as the systemic limits of variable power, land-use constraints on siting, and the need to further develop long-duration storage. This, however, would have required DOE's SunShot program to focus on transformational R&D.

Scale and ecosystem barriers also need early consideration. Scale, for example, would consider best estimates of ultimate market, an exercise that could affect the level of anticipated international cooperation, the impact of particular jurisdictional (e.g., state, regional, or national) incentives or barriers, and the availability and projected price of specific resources (e.g., rare metals). Though highly dependent on the individual technology, at least some ecosystem barriers will be initially obvious and should be considered right from the start. Fusion, for example, now in initial R&D, will produce different amounts and types of radioactive waste, depending on generator design. This presents both practical (licensing) and political questions that are best contemplated early on.[127]

3. The Most Challenging Steps Ought to Remain the Focus

The target of an effective innovation technology initiative should be to expedite the development of robust energy options through its most daunting evolutionary phases — R&D, early output, commercialization, and take-off. In contrast to the otherwise admirable ARPA-E model discussed above, government support for new zero-carbon technologies should not taper off after research and development; it must continue through NOAK-to-FOAK to take-off.

Here, as a new technology passes from early output to commercialization, it faces not one but several "valleys of death" — widened, typically, by unpredictable and often underwhelming interest and support. These valleys or gaps, shown in simplified form above in Figure 3-2, represent discontinuities over which public policy and support ought to provide a navigable bridge to the next level. Otherwise, some promising technologies are certain to fail, wasting whatever support has been provided up to that point.

In short, the R&D-to-take-off stretch of the S curve is where the most difficult, innovation-ending issues arise. Thus, it is here that the Innovation Technology Framework is most needed.

4. Policy Tools Should Fit Both the Technology and its Address on the S Curve

A framework of policies is needed to move a given technology along the S curve from conception to market. A "one-size-fits-all" approach often does not make sense. R&D, for example, will benefit from public-private partnerships, whereas policies at the commercialization stage may work better as self-activating market mechanisms. Structural reforms that alter the surrounding ecosystem can address both technology-specific challenges and broader infrastructural constraints. In a nutshell, we must design policies that address specific barriers, while at the same time supporting a technology's existing development vector — starting with its place on the curve.

One example of a highly effective demand-pull/supply-push policy combination was the R&D and tax credit program supporting unconventional natural gas. In the 1970s, DOE and the federal Gas Research Institute (GRI) began to fund R&D (a push strategy) aimed at developing unconventional gas resources, including shale gas. This helped bring to commercial demonstration scale the use of fracking and directional drilling technologies in shale deposits. In the 1980s, Congress added a pull strategy — targeted credits under the U.S. Internal Revenue Code. The tax credit program for shale gas production remained in place until 1992, with credits continuing until 2002. Those two programs, sequential but reinforcing, played a significant role in elevating this transformational energy technology to competitive scale — and they did so over a fairly short period, just 15 years.[128]

At a more general level, diffused technologies (e.g., wind and solar energy) will tend to rely on individual components that are mass produced — "commodity goods." Conversely, centralized, capital-intensive projects (e.g., carbon capture and sequestration, and nuclear energy) will gain the most from learning-by-doing and economies of scale, with particular emphasis on the best ways to integrate the technology into a larger and highly complex system that magnifies its efficiencies.[129]

Other examples of tailored policy mechanisms include:

(i) Wind and solar

- R&D demonstration programs funded in the 1970s;
- Demonstration-stage and later support provided by European nations;
- Renewable portfolio standards set by various U.S. states — a policy geared to late-NOAK and early commercialization stages; and
- Windpower production tax credits and the solar energy investment tax credits authorized by the U.S. Congress — an example of commercialization-stage policies.

(ii) Fusion energy

- Long-term R&D programs supported by federal grants and private investment.

(iii) Carbon capture and sequestration

- Late 1990s-2000s: R&D for carbon sequestration;
- 1997-2015: CCS demonstration projects at coal-fired electricity generators (e.g., FutureGen);
- 2010-present: CCS demonstrations at other carbon emitters;
- 2008: 45Q tax credits, expanded in 2022 to become commercialization-stage policies;
- 2015: CCS-based performance standards for new coal-fired power plants; and
- 2023: CCS-based performance guidelines for certain existing fossil-fueled power plants.

5. Public/Governmental Financial Support is Essential until a Technology Achieves Take-off

Underlying much of what makes energy innovation successful is the need for financial support during all of its initial stages. Multiple studies and direct experience show that those are the R&D, early output, and commercialization stages.[130] Essentially, this means that new energy technologies require continued backing — in particular, funding — until they are able to compete in the marketplace. Even so, some measure of support (e.g., a carbon tax) will (and should) extend beyond take-off.

Especially acute along the lower half of the S curve is the need to support commercial demonstrations: from first-of-a-kind (FOAK) to Nth-of-a-kind (NOAK). Policies backing early commercial demonstrations typically will focus on reducing initial technology costs, lowering private sector risk ("de-risking"), and resolving any evident ecosystem barriers. Unlike self-activating incentives, which are useful later, this support works best if structured as a public-private partnership and implemented through direct grants and subsidies (e.g., contracts for difference). As one scholar of the field has noted, during the demonstration phase it makes sense to structure financing in a way that is familiar to private investors. Particularly helpful are indirect tools like loans, loan guarantees, and tax credits. These financial mechanisms interfere minimally with commercial practice and render the project more credible to investors.[131]

As noted in Section 2, technology entrepreneurs may be unable to obtain affordable financing or to self-finance, even after successful early demonstrations at scale, due to continuing perceived risk. Sustained financial support can provide a bridge from those early projects to later ones — and even to initial market ramp-up.[132]

Promoting Quality Pre-FEED and FEED Studies

Front-end engineering design (FEED) and initial pre-FEED studies are important elements in reducing cost and lowering risk during the demonstration (early output and commercialization) period. The less financially pressed the developer is during the engineering process, the more likely it is that a first-class FEED study will emerge. This not only will reduce risk during project execution, but also will provide some construction flexibility without necessitating costly re-negotiation. Policy support is required to generate strong pre-FEED and FEED studies. An 80%-90% cost-share grant would be appropriate to tilt most project developers towards robust FEED studies.

Bundling Government Grants and Contracts

Bundling government financial and planning support across multiple projects helps to assure that a technology will survive the full demonstration process — from early output to commercialization. By creating impetus for vendors and contractors not to front-load expenses, it will also reduce the costs and risks of the initial project. The same reasoning applies to engineering, where design variations can be spread across several projects, allowing standardization to evolve organically, while optimizing learning-by-doing.

Support here can be in the form of cost-share grants, contracts for difference, or straight-out technology procurement by government contract. These instruments can be bundled to provide more certainty that a technology will proceed through all stages of the demonstration process. For example, a subsidy could be awarded for three sequential projects involving the same technology type, provided that each project meets specified performance metrics before the next commences. This arrangement would allow the developer to negotiate more favorable terms with financiers and with engineering, procurement, and construction (EPC) firms, lowering overall costs and risks to each.

Coordinating Private-Sector Requests for Proposals (RFPs)

The private sector also can design strategies that help to traverse the entire demonstration process — FOAK to NOAK, and beyond — either standing alone or as complements to government programs. For example, customers seeking to commercialize a technology could develop a common RFP that meets specific cost and performance criteria. They then could bundle their RFPs, helping to assure that a technology vendor who has met these criteria for past projects will be approved for the next one. Or they could simply issue a common RFP and allow each customer to negotiate directly with the vendor for each project. (These arrangements may require policy support in the form of exemptions from antitrust measures that otherwise could apply to buyer-coordinated contracts.[133])

Creating New Institutions to Support Product Development

As with R&D, early output and commercialization could benefit from new institutions. One approach, recommended by ITIF, would create an office of major demonstrations within U.S. DOE.[134] A second would be to develop a build–own–transfer business model, where a government-sponsored corporation would cover a large percentage of total investment before transferring ownership to a private-sector entity.[135] This model reduces development-phase risks, because the corporation would not transfer a project until fabrication or construction had been completed and the technology (a plant or another complex installation) was up and running. Yet a third suggestion for bridging "the demonstration gap" would establish regional funding authorities, supported by electric power system benefit charges or carbon mitigation programs, and incentivize them through federal grants. This would offer geographic variation in innovative ideas, and a potential way to circumvent political gridlock at a higher level.[136] However constituted, these new institutions would expressly focus on shepherding multiple technologies across the second and third valleys of death (see Fig. 3-2 above). In effect, they would serve as the right-hand "bookend" of the development process, opposite ARPA-E, with traditional R&D in the middle.

6. Policy Mechanisms Must be Simple, Clear, and, at the Commercialization Stage, Self-Executing

Policies should be written to be as simple and clear as possible, at all stages. Those designed for the commercialization stage, however, face particular challenges.

Commercialization covers a broad range. It starts after the FOAK-to-NOAK period, may proceed through a number of projects after that, and tails off only when market "take-off" happens — possibly not until tens or even hundreds of innovative items (plants, projects, components) have been successfully launched into the stream of commerce. At this stage, innovation policy must help animate a smooth "hand-off' to the market, which entails shepherding the technology to a level of deployment sufficient to satisfy several key conditions. The most critical involve:

- Driving the technology significantly down the cost curve;
- Increasing deployment speed by creating manufacturing supply chains and, to the full extent possible, "commoditizing" the technology; and
- Generating a sufficient level of committed financing to lower the cost of debt and equity.

Adopt Simple and Predictable Financial Incentives Scaled to Drive Multiple Projects

To maintain an efficient approach to technology take-off, incentive policies should be as simple, certain, and as wide scale as possible. Production tax credits can meet these criteria, if properly designed. Key features:

- Producers are able to claim credits without prior government review and approval, based on clear eligibility criteria;
- Credits are available based solely on performance;
- Credits are directly refundable;
- Windows for eligibility and use are communicated clearly in advance and remain open for a sufficiently long period; and
- Non-compliance is identified via transparent reporting requirements, backed by a credible threat of audit and, if necessary, claw-back.

Feed-in tariffs (FITs) have played a similar role in providing developers with certainty that, if their projects perform as advertised (usually measured in terms of kWh output), they will promptly receive their incentive payments.

Other policies work in similar fashion. Although not as self-executing as a tax credit, a contract for difference (CfD) pegged to an energy or carbon price can also offer certainty and be applied widely. This approach has been used in the U.K. to develop early commercial demonstrations. Applying it during the commercialization phase would significantly broaden its utility and further distribute government support. With increases in project volume, financial standardization will also increase, while learning curves shorten. As a result, the cost of debt and equity decreases; so does risk. As this happens, per-project government outlay will shrink.

Demand-pull policies that require emissions reductions or set a carbon price also play an obvious role. In the U.S., however, technology-based emissions performance standards remain highly industry specific; they do not apply across the entire energy sector. For that reason, targeted financial incentives will continue to be important, particularly for control technologies at earlier points in the commercialization phase.

7. Public communication should clearly differentiate between the demonstration stage and the FOAK-to-NOAK progression — with narrative built from on-the-ground examples of learning-by-doing

One potentially serious issue arises out of a public perception that innovation technologies which have moved beyond R&D should function as they are eventually expected to do in the market. But that is not how the innovation process works. This becomes especially problematic when observers fail to distinguish between demonstration projects (or even earlier, and smaller, pilot projects) and initial market-scale exemplars — that is, the first-of-a-kind (FOAK) installation and a number of potential follow-ons, up to Nth-of-a-kind (NOAK).

The key is to communicate an understanding of what is at stake at each phase — and to construct a narrative around on-the-ground examples of learning-by-doing which advance goals appropriate to that particular phase.

At the demonstration level, as a recent report has it, the goal is to deploy a solution "(a) in the relevant environment, (b) at the smallest scale needed to prove that the technology works at scale, and (c) for the purpose of demonstrating 'whatever the industry is most afraid of.'"[137]

Although the line between demonstration and FOAK can at times be less than crystal clear, the latter is intended to be a full-scale, commercial-level project expected to earn revenues, become operational on time and within budget, and mark the beginning of a solid track record. It also is intended to produce a specified output, one that at least serves a niche market.

The problem is that projects along this progression must first meet a far more relevant goal: to reach, express, and surmount critical learning thresholds.[138] These range from whether the basic technology works at all, to whether the required level of debt and equity financing will become available.

When the public and its representatives come to believe in the fiction that, to be worthy of support, projects must fully succeed at every level, the need for clear, yet more nuanced communication is apparent. But to move beyond this simplistic narrative requires deeper understanding of the process: that, at each stage — pilot, demo, trial, FOAK, NOAK(s) — palpable progress is required, but complete and utter triumph is not. Echoing the words of MIT's John Deutch, "energy innovation is constrained not by an absence of new ideas, but by the absence of early examples of successful implementation."[139] To discern and describe those initial successes, new and more convincing narratives are called for.[140]

8. Success Requires that Key Ecosystem Barriers Be Identified and Addressed

Ecosystem constraints are, to some extent, the odd duck. The other three major success levers discussed in Section 3 — lower costs, faster project deployment, and easier access to capital — integrate relatively well into specific policies tailored to a given innovation's particular development stage. Ecosystem barriers, however, are broader. They include tangibles, such as the ability to physically connect to existing infrastructure (e.g., a high-efficiency lightbulb that works in existing household sockets), as well as more general and abstract concerns, such as the regulatory and commercial rules, standards, and practices that facilitate market access. They also include less measurable, but still very real considerations, such as political temperature and public acceptance. These less-well-defined considerations can affect specific technologies (e.g., fusion), or more broadly influence the pace and scale of a new, zero-carbon energy system.

Moreover, ecosystem barriers can involve structural issues that range from narrow to broad, and everywhere in between. Take nuclear energy. The scope of the relevant ecosystem can have a huge influence on strategy. An example of a relatively narrow concern is the need for specific tweaks in the regulations of the U.S. Nuclear Regulatory Commission addressing the licensing of small, modular reactors. An example of a broad barrier is the growing lack of advanced nuclear engineering expertise in major industrial cultures (e.g., the U.S.) and its impact on the development of next-generation nuclear plants (both their timing and which nations will lead in their production). And barriers can exist in between these extremes. A few examples: (i) public opposition to nuclear energy in any form; (ii) state-based clean energy policies that disadvantage nuclear relative to wind and solar; (iii) the failure to make headway in addressing the need for long-range storage of high-level nuclear waste; (iv) lack of coordination between the development of next-generation nuclear (or the continued use of existing nuclear units) and the projected sharp increase in electricity demand over the next three decades; and (v) inattention to the potential synergies between expanded production of hydrogen as a fuel and the expansion of nuclear energy. And these examples just scratch the surface.

Specific Barriers and their Removal

Some ecosystem issues are well defined and can be addressed through targeted innovation policy.

Carbon capture, for example, stands early in the development stage. In addition to an up-front financial boost, workable CCS requires systems of pipelines and vetted storage sites, among other infrastructure. The 2021 Infrastructure Investment and Jobs Act (IIJA), discussed above, is an example of this type of targeted effort. It provides nearly $5 billion for CO_2 pipelines and saline storage sites. And the SCALE Act,[141] now folded into the IIJA, establishes grant and loan guarantees for carbon dioxide pipelines as well as expanded initial saline storage hubs.

Nuclear technology, on the other hand, is evolving into advanced designs, locations, and business models. Generation IV nuclear fission reactors require a permitting process that better accommodates their future, more modular shape. Right now, a revamped regulatory system around permitting is a critical path item for moving this technology forward.

Wind power faces substantial barriers in land-constrained regions. An example is Japan, where on-shore wind energy has stalled. Obstacles include the lack of available flat land offering sustained winds, a highly segmented national power grid with weak domestic interconnections, and isolation from international power systems. For the future, analysts point to the island nation's massive offshore wind resource, which could become available with advances in cost-competitive floating tower technology.[142]

Solar PV, exclusively on land, may encounter hard physical limits. The recent Princeton Net-Zero study found that, for its most ambitious U.S. zero-carbon scenario, solar would require an area slightly larger than that of Maryland, spread across 15 sunny states, including a number solely offering tracts that are highly disaggregated and fragmented — thus increasing the likelihood that siting will be complex, slow, and expensive.[143]

More generally, ecosystem barriers demand broader strategies. This can include an umbrella policy or set of policies (e.g., the IIJA), repair of outdated regulations (e.g., for generation IV nuclear reactors), the adoption an energy technology that sidesteps a particular barrier (e.g., offshore wind in the face of land constraints), or, at times, the prompt recognition that a given technology has its limits and that a different one may be more suitable (e.g., CCS rather than solar PV in northern industrialized areas). Here are some ways these barriers can be removed:

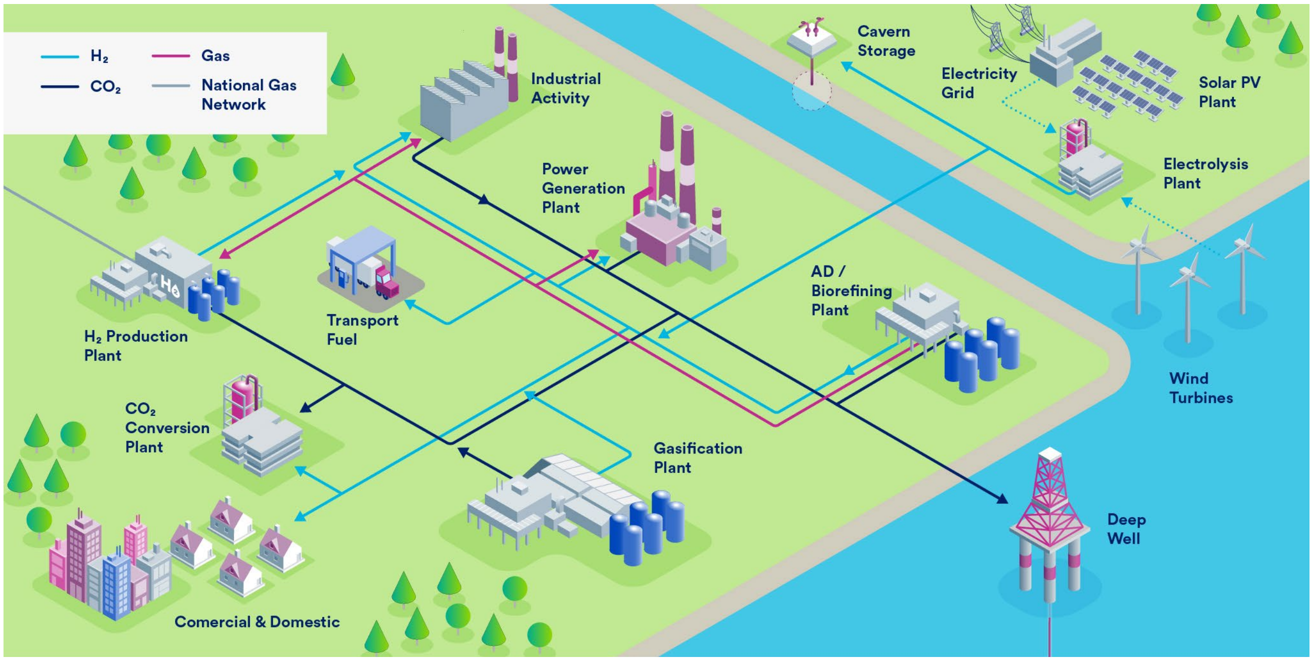
- ***Create policies*** that address ecosystem barriers. Example: Deal with licensing issues now to eliminate delays in siting Gen IV nuclear units.
- Design ***different technology pathways*** to eliminate bottlenecks. Example: Increase support for superhot rock geothermal, which, unlike wind and solar, promises to be both energy-dense and fully dispatchable, overcoming transmission and energy-storage needs that can significantly constrain variable renewables.
- Develop ***complimentary infrastructure*** resources in parallel, to eliminate bottlenecks. Examples: Build fueling stations to dispense hydrogen; create incentives to deploy heavy trucks powered by hydrogen; size pipelines and storage sites to accommodate the growth of carbon capture and sequestration technologies.
- Direct ***first applications to niche areas*** that face fewer ecosystem bottlenecks and that provide early, potentially scalable opportunities. Example: Focus initially on using zero-carbon fuels in marine shipping, which requires less extensive fueling infrastructure than trucking or other land-based transportation modes.[144]
- ***Plan around projected diffusion delays*** caused by ecosystem barriers. Example: Identify potential bottlenecks (and work-arounds) as part of overall planning to achieve climate goals.

Moving towards Systems Planning

To address issues at larger scale, innovation policy must incorporate aspects of systems planning. An example of the challenge: estimates indicate that European transmission lines will have to increase four-fold to meet the EU's 2030 goal of 55% carbon reduction. Yet Germany has been struggling unsuccessfully for over a decade to build a single north-south, high-voltage connector to better address the projected need. And that is just one case. Expanding transmission at decarbonization scale will require a pace and scope — and central systems planning —that most OECD countries have not attempted for decades.

The U.K., conversely, is working on an integrated energy network that puts a premium on systems planning, albeit at a regional level. The Tees Valley project is promoting clean hydrogen in a way that foregrounds the interaction between production, distribution, and end use. Agencies and private firms located south of Newcastle-upon-Tyne in northeast England are in the process of designing an integrated hydrogen and CO_2 production network on a 4,500-acre industrial parcel abutting an international port (see Fig. 4-4,[145] below). Essentially, for hydrogen, this pilot community will become a hub of production, pipeline and ocean transport, as well as end use. This coordinated, "cross-silo" approach — which includes local industries and major energy companies, with funding support from a new national-level research and innovation agency — is designed to help identify and address the structural issues that can undermine success.

Figure 4-4: Plans of the Tees Valley Combined Authority for an integrated H_2, CO_2, and CH_4 production and distribution network in a heavily industrial port area 30 miles south of Newcastle-upon-Tyne, England



9. Nationally, this Transition Will Require Business, Finance, and Government to Apply Industrial Policy to Innovation Technology

At times, the primary institutional actors that move innovative energy technologies up the S curve coordinate adequately or at least proceed in parallel fashion. But they often do not. This causes major inefficiencies, leading to a form of gridlock in which participants are able to see themselves at the forefront of decarbonization, while failing to actually decarbonize. The result can be a herd of "white elephants" — projects that have received significant support from one sector (often the U.S. government or a key agency such as DOE), but without backing from other sectors find themselves unable to progress towards take-off.[146]

The challenge here is how to create and formalize industrial policy around decarbonization, but within the context of market economies. Specifically, a national plan is needed to coordinate the efficient use of resources to reach climate goals. In this context, the key element is institutional: coordinating the private sector, particularly the financial sector, with public agencies and the research community to reach a common objective. Industrial policy can range from top-down, government-directed planning to more flexible approaches — but ones that still require coordinated participation of the major actors around broad, long-term policies and goals. In addition, it should look at the industrial sector as a whole to ensure that all options (e.g., CCS, hydrogen, and electrification) are available in each industrial sector.

Specific examples of this type of coordination could include one or more of the following:

- ***A bipartisan or multi-party commission*** to recommend an innovation technology plan for a zero-carbon energy system. The commission would include representatives of business, finance, academia, and relevant government agencies.
- ***A public-private corporation*** at the national or regional level(s) that would formulate integrated energy technology policy for the states or discrete sub-national regions. If the latter, the entity might focus (at least in the U.S.) on somewhat different zero-carbon energy mixes, depending on geography and public sentiment. One area might favor wind, another solar, a third, carbon capture, and a fourth, nuclear.

- Related to the preceding, ***zero-carbon goals set at the state or regional level***, tied to funding and other policy support primarily directed by the federal government, in conjunction with the private sector.
- ***V. 2.0 of ARPA-E***, with particular attention to the demonstration and FOAK-to-NOAK (early output) period along the curve of innovation. This would include meaningful participation of the private sector, particularly financial players.
- ***A long-term energy technology plan*** (over, say, 25-40 years) with legal and institutional guardrails that would render it relatively safe from jarring, inconsistent alteration — allowing all major interests to act in reliance on a more predictable energy policy future.
- ***A separate agency dedicated to arresting climate destabilization*** and coordinating energy innovation technology to address it over the long term.
- ***A pollution tax or other market-based mechanism*** — perhaps after significant rollout of inexpensive electric vehicles — that guides the market and major players toward other innovative zero-carbon energy technologies.[147]
- ***Federal action to "pick winners"*** — if not specific companies, specific technologies and promising technological areas — and then to design public policy (and public recognition) around those choices. This also could be done on a regional level.

10. Internationally, Innovation Policy Requires Integrated Leadership from those Nations, Multinational Institutions, and Global Corporations Best Positioned to Move Energy Technologies Forward

The innovation framework described here must ultimately be global in scope. This implies that technology development and deployment will be occurring around the world. To an extent, this is true.

Wind and solar PV serve as an example of how international policies and business models can drive technology forward. Both the U.S. and Germany provided PV with substantial incentives to lower costs and create stable demand, thus seeding the market. Manufacturers in China played a significant role in scaling up the global supply chain and further cutting PV costs. As a result, solar photovoltaics is at the point of being cost competitive for incremental demand. But this has also created tensions around trade policy.

Given the growing risks posed by climate change, one focus might be on relatively narrow collaborations among the key players — nations, multinational institutions, and global corporations — best positioned to advance decarbonizing technologies. In particular, this would include those posting a strong innovation track record, benefiting from top-level support for zero-carbon solutions, and offering distinct synergies with other members of the group.

Alternative ways also exist for international collaboration on innovation technology policy to become more intentional over the long term. The recent revival of the U.S.-China climate change working group is one example of potentially beneficial collaboration on R&D and commercial demonstration projects.[148] Innovation policy also could become part of collaborations between OECD and emerging economies. For example, the African Rift provides an ideal location to develop advanced geothermal technology — it offers favorable geology as well as commercial experience in geothermal development. Building infrastructure to support zero-carbon marine fuel could be coordinated across ports globally. Technology expansion policies can help to ensure early deployment of zero-carbon energy as part of the international development commitments (INDCs) of the nations that signed the 2015 Paris Accords.

Identifying such opportunities and encouraging collaboration should become a joint endeavor of the Clean Energy Ministerial (CEM), the 29-member multilateral clean energy leadership and action platform.[149] Multinational collaborations like these greatly increase the likelihood that key zero-carbon technologies will achieve wide use.

And wide use is the goal — without it, efforts to address climate change will likely fail.

APPENDIX A

Our Core Team

Lee Beck

A German citizen with wide experience in EU energy policy, Lee Beck is CATF's senior director in Europe and the Middle East, leading CATF's climate strategy to promote a broad portfolio of solutions in both regions. Lee has also been responsible for advancing CATF's efforts on the global climate policy stage through CATF's presence at COP28 in the UAE and at COP27 in Egypt. Before stepping into her current role, she was CATF's global director for carbon capture. Under her leadership, the carbon capture team played an integral role in promoting cutting-edge carbon management policies globally. Lee also serves as a Senior Fellow at the Atlantic Council's Global Energy Center. Prior to joining CATF, Lee was a senior advisor at the Global CCS Institute, where she led its advocacy efforts in North America.

Jeff Brown

Jeff is currently a Research Fellow at the Steyer-Taylor Center for Energy Policy at Stanford University. He was formerly Senior Vice President of Finance at Summit Power, where he was in charge of obtaining project financing for wind, solar, gas, integrated gasification combined-cycle, and carbon-capture projects. Previously, Jeff had 26 years of experience in energy and infrastructure project finance, debt capital markets, and financial/commodity derivatives while at Goldman Sachs and Merrill Lynch, where his clients included a variety of utilities, pipelines, transportation projects, U.S. states, and sovereign oil companies.

Joe Chaisson

As CATF's Research and Technical Director, Joe has led CATF's research and technical work since its founding in 1996. He has commissioned and supervised more than $20 million of direct research on behalf of CATF in the last decade. During a 35-year energy policy career, Joe has authored, co-authored, or supervised hundreds of energy and environmental studies and analyses. He works closely with technology companies and financial entities to evaluate and help develop and deploy emerging technologies.

Dr. Douglas Cortez

Doug has over 45 years of experience in the electric power, petroleum processing, and chemical production industries, working in the fields of technology research and development, project development, project financing, and engineering and construction. As vice president at the Fluor Corporation, he contributed to the development of hundreds of power, cogeneration, and alternative energy projects. He was active in developing and evaluating environmental control technologies, including the development of Fluor's post-combustion carbon-capture technology. Since 2006, he has been managing director of Hensley Energy Consulting LLC. Doug has worked with energy and mining companies, as well as developers of clean energy technologies and commercial projects, and advised private equity investors and other financial institutions. He has been an advisor to and expert public witness for Clean Air Task Force and several other environmental NGOs.

Eric Ingersoll

Eric is an entrepreneur, technology developer, and strategic advisor with more than 20 years of experience in the energy sector, particularly in the areas of technology development, venture creation, and investment and acquisition strategy. Until 2013, he was a founder and CEO of General Compression, a utility-scale energy storage company that raised $100 million. Eric was honored as a Champion of Change at the White House for his renewable energy work. He recently led an assessment for the U.K.'s Energy Technology Initiative on the cost drivers of nuclear energy and is currently a member of MIT's Future of Nuclear study. He is a founder and Managing Director of the Energy Options Network (EON) and is a former member of the board of Clean Air Task Force.

David Mohler

David served as Deputy Assistant Secretary within the Office of Fossil Energy at the U.S. Department of Energy (DOE) under President Obama and was responsible for DOE's R&D programs in CCS, advanced fossil energy systems, and large demonstration projects. Previously, he served as Senior Vice President and Chief Technology Officer for Duke Energy, with responsibility for technology development across the energy spectrum, including renewable, nuclear, fossil, and grid-related technologies. David also is a Senior Fellow at Clean Air Task Force.

Robert (Rusty) Russell

Rusty is a lawyer and environmental consultant who has worked extensively with CATF as well as with other environmental NGOs. He also has written about and taught environmental and energy law and policy at a number of universities and law schools in the New England. He is the lead author of this report.

John Thompson

John is CATF's Technology and Markets Director and the primary lead for this Report. Starting in 2001, John directed CATF's efforts on CCS research and advocacy in the United States and China before focusing more broadly on innovation technology strategy. In his earlier work, he focused on project development needs and the process of getting "steel in the ground," which included a leadership role in advocating for several CCS projects. John has authored several economic analyses and policy reports on CCS technology deployment, and his work has contributed to the development of innovative business models and strategies. He is the director of the project that led to this report.

Kurt Waltzer

Kurt is the principal of Energy Systems Innovation and a senior CATF advisor. His work centers on engaging with civil society, market leaders, and policymakers to advance systems-level solutions for the most challenging aspects of decarbonization. Previously, Kurt was CATF's CEO and managing director, where he focused on growing the organization from a US-based NGO to one with a global profile, while expanding CATF's scope to encompass a wide range of decarbonization technologies. For the past two decades, Kurt also has worked to promote carbon capture and storage technology, playing a leading role in developing the policy foundation and supportive network that led to adoption in the U.S. of major CCS policies. Kurt holds an MBA from the University of Michigan and bachelor's degrees in economics and biology from Ohio State.

Project Director: John Thompson

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Graphic Design: 5IVE

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[31] Weiss, C. & Bonvillian, W. (2009). *Structuring an Energy Technology Revolution* (Cambridge, Mass.: MIT Press) (p. 1) ("…market forces alone cannot provide the pace and scope of innovations required to meet the urgent national need for improved technology for energy supply and efficient end use, and to overcome the huge built-in preferences for existing technologies."). Demand-pull (and supply-push) policies are discussed in more detail in Sec. 3 below.

[32] Diana Godlevskaya, D., Galik, C. & Kaufman, N. (2021, December 17). Major U.S. electric utility climate pledges have the potential to collectively reduce power sector emissions by one-third (pp. 1743-1744). *One Earth.* 4, 1741-1751. https://doi.org/10.1016/j.oneear.2021.11.008; See Clean Air Task Force (n.d.). *State Technology-Inclusive Clean Energy Standards and Corporate Commitments.* https://www.catf.us/wp-content/uploads/2020/10/State-Actions-and-Utility-Pledges-1.pdf

[33] A number of these are documented. See Cohen, L. & Noll, R. (1991). *The Technology Pork Barrel* (Washington, DC: Brookings Institution Press).

[34] Public Law No. 111-5, 123 Stat. 115 (H.R. 1 in the 111th Congress), signed into law on Feb. 17, 2009. https://www.congress.gov/bill/111th-congress/house-bill/1/text

[35] Doerr, J. (2021). *Speed and Scale: An Action Plan for Solving Our Climate Crisis Now* (New York: Portfolio/Penguin) (pp. 266-267) (at a default rate this low, lenders would have earned "monstrous profits" had the loans been issued at ordinary commercial rates).

[36] Doerr, J. (2021). *An Action Plan for Solving Our Climate Crisis Now* (New York: Portfolio/Penguin) (pp. 261, 266-267)("Most startups fail.").

[37] Unless noted, data and quotes here are from Lester, R. & Hart, D. (2015, Winter). Closing the energy- demonstration gap. *Issues in Science and Technology*, 31(2), 48-54. https://issues.org/closing-the-energy-demonstration-gap-2

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[39] In such a case, the threshold would be far lower than 1%-2.5% of global energy, but perhaps more than that range for the percentage of the submarket.

[40] Kramer, G. & Haigh, M. (2009, December 3). No quick switch to low-carbon energy. *Nature*, 462(7273), 568-569. https://doi.org/10.1038/462568a

[41] Bento, N. & Wilson, C. (2016, December). Measuring the duration of formative phases for energy technologies. *Environmental Innovation & Societal Transitions*, 21, 95-112. https://doi.org/10.1016/j.eist.2016.04.004

[42] *Id.,* p. 107.

[43] Smil, V. (2016, October 4). Examining energy transitions: a dozen insights based on performance (pp. 194-197). *Energy Research & Social Science* 22, 194-197. http://dx.doi.org/10.1016/j.erss.2016.08.017

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[45] Azevedo, I., et al. (2020, May/June). The paths to net zero; how technology can save the planet (p. 19). *Foreign Affairs*, 99(3), 18-27. https://www.foreignaffairs.com/world/paths-net-zero

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[47] Weiss, C. & Bonvillian, W. (2009). *Structuring an Energy Technology Revolution* (Cambridge, Mass.: MIT Press) (p. 15).

[48] Fri, R. & Savitz, M. (2014, March). Rethinking energy innovation and social science (p. 184). *Energy Research & Social Science*, 1, 183-187. http://dx.doi.org/10.1016%2Fj.erss.2014.03.010

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[50] Doerr, J. (2021). *Speed and Scale: An Action Plan for Solving Our Climate Crisis Now* (New York: Portfolio/Penguin) (p. 270).

[51] Cherp, A., et al. (2021, July 19). National growth dynamics of wind and solar power compared to the growth required for global climate targets. *Nature Energy*, 6, 742–754. https://doi.org/10.1038/s41560-021-00863-0

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91 International Energy Agency (IEA). (2022, October). *World Energy Outlook 2022* (p. 316). https://www.iea.org/reports/world-energy-outlook-2022; Ritchie, H. (2023, April 3). *How Long Does It Take to Build a Nuclear Reactor?* [blog]. Retrieved February 2, 2024, from https://www.sustainabilitybynumbers.com/p/nuclear-construction-time

92 A particular, related example is the French nuclear program, whose 56 operating units generate more than 70% of that nation's electricity. Most of the plants that have operated went on line during a 15-year period, 1979-1994 (56.5 GW of 66.8 GW). Standardized designs were key — when employed, construction time averaged 5.7 years. But that has increased with newer, more complex permutations. The single French unit remaining under construction, Flamanville 3, will sport one of Europe's newest designs (EPR Framatome-Siemens).

Work broke ground in 2007; the unit's estimated date of operation, recently pushed back again, is mid-2024. Grübler, Arnulf, "The French Pressurized Water Program," Ch. 24 in Grübler, A., Wilson, C., eds. (2014). *Energy Technology Innovation; Learning from Historical Successes and Failures* (New York: Cambridge U. Press); World Nuclear Association. (2022, September). *Nuclear Power in France* (in February, 2022, the government announced plans to build six new reactors, and to consider building another eight). https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/france.aspx; Van Overstraeten, B. & Mallet, B. (2022, January 12). *EDF Announces New Delay and Higher Costs for Flamanville 3 Reactor.* Reuters. https://www.reuters.com/business/energy/edf-announces-new-delay-higher-costs-flamanville-3-reactor-2022-01-12/

93 Flyvbjerg, B. (2021, November/December). Make Megaprojects More Modular (p. 52). *Harvard Business Review*, 58-63. https://hbr.org/2021/11/make-megaprojects-more-modular

94 See *Id.* (Japan's $12 billion totally custom-designed Monju experimental breeder reactor was abandoned after 30 years; it operated for one hour during its 22-year lifetime; decommissioning is expected to cost another $3.4 billion and not be complete until 2047).

95 U.S. Energy Information Administration (EIA). (2022, March 4). *FAQs; What Is U.S. Electricity Generation by Energy Source?* (in Feb. 2022, wind and PV accounted for more than half of all renewable generation in the U.S., with wind in first place. Of total MWh: wind (9.2%), hydropower (6.3%), PV (2.8%), biomass (1.3%), geothermal (0.4%), and solar thermal (0.1%)). https://www.eia.gov/tools/faqs/faq.php?id=427&t=3

96 Sivaram, V., Cunliff, C. & Friedman, J. (2020, September 15). *To confront the climate crisis, the U.S. should launch a National Energy Innovation Mission*. MIT Technology Review (in 2019, venture capitalists invested only $1 billion in energy companies, compared with $20 billion in biotech and $70 billion in information technology). Retrieved October 4, 2022, from https://www.technologyreview.com/2020/09/15/1008406/climate-crisis-energy-innovation-mission-us-election-tech-policy-opinion

97 Chong, H. (2022, January). *Mission Critical: the Global Energy Innovation System Is Not Thriving* (p. 7). Information Technology & Innovation Foundation (ITIF). https://itif.org/sites/default/files/2022-global-index.pdf; Chong, H. & Hart, D. (2021, October 29). *Wheezing Toward Glasgow: The Parlous Health of the Global Energy Innovation System* (venture capital has made a comeback sine 2017 in the global energy innovation area, but the vast percentage of investment has been in only a few, mostly corporate-dominated areas: electric power trains, energy storage, and energy efficiency). https://itif.org/publications/2021/10/29/wheezing-toward-glasgow-parlous-health-global-clean-energy-innovation-system

98 Gaddy, B., et al. (2017, January 1). Venture capital and cleantech: the wrong model for energy innovation. *Energy Policy*, 102(C), 385-395. http://doi.org/10.1016/j.enpol.2016.12.035

99 Adner, R. & Kapoor, R. (2016, November). Right Tech, Wrong Time. *Harvard Business Review*, 60-67. https://hbr.org/2016/11/right-tech-wrong-time Adner, R. & Kapoor, R. (2016, April). Innovation ecosystems and the pace of substitution: Re-examining technology S-curves. *Strategic Management Journal*, 37(4), 625-648. http://dx.doi.org/10.1002/smj.2363

100 Smil, V. (2021). *Grand Transitions; How the Modern World Was Made* (New York: Oxford U. Press) (p. 140) (but transition from incandescent light bulbs to LED lighting is taking 150 years).

101 Adner, R. & Kapoor, R. (2016, November). Right Tech, Wrong Time. *Harvard Business Review*, 60-67. https://hbr.org/2016/11/right-tech-wrong-time

102 Adner and Kapoor implicitly acknowledge this in an earlier study that provides the basis of their piece in the *Harvard Business Review*. See Adner, R. & Kapoor, R. (2016, April). Innovation ecosystems and the pace of substitution: re-examining technology S-curves (pp. 4, 11-12). *Strategic Management Journal*, 37(4), 625-648. http://dx.doi.org/10.1002/smj.2363

103 See *id.,* p. 35. Adner and Kapoor point out that this may be especially critical in Case 3, where emergent challenges are high, but existing technology has little room for improvement. Public policy (e.g., RD&D funding) may be required to move innovation forward and avoid market stagnation.

104 These are sometimes referred to as carbon capture and storage (CCS) or carbon capture, use, and storage (CCUS) facilities.

105 Weiss, C. & Bonvillian, W. (2009). *Structuring an Energy Technology Revolution* (pp. 11-12) (Cambridge, Mass.: MIT Press); Delucchi, M. & Jacobson, M. (2011, March). Providing all global energy with wind, water, and solar power, part II: reliability, system and transmission costs, and policies (p. 1179). *Energy Policy*, 39(3), 1170-1190 ("We recognize that historically, changes to the energy system, driven at least partly by market forces, have occurred more slowly than envisioned here… . However, our plan is for governments to implement policies to mobilize infrastructure changes more rapidly than would occur if development were left mainly to the private market."). http://doi.org/10.1016/j.enpol.2010.11.045

106 Samant, S., Thakur-Wernz, P. & Hartfield, D. (2020, February). Does the focus of renewable energy policy impact the nature of innovation? Evidence from emerging economies (p. 2). *Energy Policy*, 137, 1-12. http://dx.doi.org/10.1016/j.enpol.2019.111119

107 Because they are conceptual categories, there is overlap — sometimes a given approach both pushes and pulls. Tax credits, for example, can stimulate demand or enhance supply (or both) — depending on how they are structured. Nonetheless, this analytic distinction facilitates deeper understanding of how an Innovation Technology Framework operates — and how to best design one.

108 Hart, D. (2017, July). *Across the "Second Valley of Death": Designing Successful Energy Demonstration Projects* (p. 7). Information Technology & Innovation Foundation (ITIF). https://www2.itif.org/2017-second-valley-of-death.pdf

109 California Air Resources Board (CARB). (2021, August 20). *Advanced Clean Trucks Fact Sheet*. ("Manufacturers who certify Class 2b-8 chassis or complete vehicles with combustion engines would be required to sell zero-emission trucks as an increasing percentage of their annual California sales from 2024 to 2035, when zero-emission truck/chassis sales would need to be 55% of Class 2b to 3 truck sales, 75% of Class 4 to 8 straight truck sales, and 40% of truck tractor sales."). Retrieved October 7, 2022, from https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-trucks-fact-sheet

110 The Maritime Executive. (2022, June 6). *Eastern Pacific Signs MOU for Industry's First Ammonia-Fueled Vessel*. https://www.maritime-executive.com/article/eastern-pacific-signs-mou-for-industry-s-first-ammonia-fueled-vessel

111 International Marine Organization (IMO), Marine Environment Protection Committee (MEPC). (2023, July 7). *2023 IMO Strategy on Reduction of GHG Emissions from Ships* (sec. 3.3.4). https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC%2080/Annex%2015.pdf

112 For more detail on the VTR program, *see* Idaho National Laboratory, https://inl.gov/vtr

113 The conceptual design approved in September 2020 is based on a 300 MW-thermal pool-typed, sodium-cooled reactor fueled by a Uranium-Plutonium-Zirconium ternary metallic alloy. This fuel, although not widely used, is one that U.S. DOE has sufficient experience with and understanding of through its EBR-II program. Walter, C., Golden, G. & Olson, N. (1975). *U-Pu-Zr Metal Alloy: a Potential Fuel for LMFBR's*. Argonne National Laboratory. https://doi.org/10.2172/7138403

114 Congressional appropriation through fiscal 2023 appears limited to non-existent. If so, the project will be put on hold until at least some funding is authorized — essentially adding two years to the projected four-year schedule. This means that the earliest a VTR reactor would be operational is 2028.

115 Germany, for example, overhauls its renewable energy law (*das Erneuerbare-Energien-Gesetz*, or EEG) every two years to account for and reflect real-world market conditions.

116 International Energy Agency (IEA). (2023, May). *World Energy Investment 2023* (pp. 134-135) (some R&D includes spending on demonstration projects; state-owned enterprise funds account for a significant share of the Chinese total). https://www.iea.org/reports/world-energy-investment-2023

117 Smith, C. & Hart, D. (2021, October 18). *The 2021 Global Energy Innovation Index: National Contributions to the Global Clean Energy Innovation System*. Information Technology & Innovation Foundation (ITIF). https://itif.org/publications/2021/10/18/2021-global-energy-innovation-index-national-contributions-global-clean/; International Energy Agency (IEA). (2020, July 7). *Public Energy R&D as a Share of GDP in Selected Countries, 2012-2019*. https://www.iea.org/data-and-statistics/charts/public-energy-r-and-d-as-a-share-of-gdp-in-selected-countries-2012-2019 (IEA's 2019 data for public R&D as percentage of GDP: Japan (0.053); China (0.047); EU (0.047); U.S. (0.037)). Of the 24 nations studied by ITIF that signed the 2015 Mission Innovation pledge to double green energy research, development & demonstration funding within five years, only one (Chile) achieved it; the rest fell far short.

118 International Energy Agency (IEA). (2022, May 17). *Total Public Energy RD&D Budgets per Thousand Units of GDP by Country for 2021*. https://www.iea.org/data-and-statistics/charts/total-public-energy-rd-and-d-budgets-per-thousand-units-of-gdp-by-country-for-2021; see Sivaram, V., Cunliff, C. & Friedman, J. (2020, September 15). *To confront the climate crisis, the U.S. should launch a national energy innovation mission*. MIT Technology. Retrieved October 4, 2022, from https://www.technologyreview.com/2020/09/15/1008406/climate-crisis-energy-innovation-mission-us-election-tech-policy-opinion

119 Doerr, J. (2021). *An Action Plan for Solving Our Climate Crisis Now* (New York: Portfolio/Penguin) (pp. 231-232, 244) (noting that ARPA-E's "stamp of approval" carries considerable weight among private innovation project investors).

120 Hart, D. & Kearney, M. (2017, November 15). *ARPA-E: Versatile Catalyst for U.S. Energy Innovation* (p. 9). Information Technology & Innovation Foundation (ITIF). https://itif.org/publications/2017/ 11/15/arpa-e-versatile-catalyst-us-energy-innovation. As noted, however, ARPA-E's focus is on R&D, not commercialization and take-off. Thus, an institutional model of the type suggested by this Report would need to expand on the ARPA-E program.

121 Bonvillian, W. & Van Atta, R. (2019). *ARPA-E and DARPA; Applying the DARPA Model to Energy Innovation* (Ch. 13 (pp. 361-434) in Bonvillian, W., Van Atta, R. & Windham, P., eds. (2019). *The DARPA Model for Transformative Technologies; Perspectives on the U.S. Defense Advanced Research Projects Agency* (Cambridge, U.K.: Open Book Publishers) (p. 402) (…"the private sector views the ARPA-E project selection process as rigorous and sound enough that it is prepared to fund projects emerging from that process.").

122 U.S. Department of Energy, Advanced Research Projects Agency – Energy (ARPA-E). (n.d.) *Our Impact*. https://arpa-e.energy.gov/?q=site-page/arpa-e-impact

123 Ma, M. (2022, September 3). *Inside the Small Federal Agency Funding the Biggest Climate Moonshots; ARPA-E Is Quietly Backing Some of America's Riskiest — and Most Promising — Climate-Saving Tech*. Protocol (agency has provided over $3 billion to more than 1,300 projects, of which 190 have collectively received over $10 billion in private-sector follow-on funding). https://www.protocol.com/climate/arpa-e-moonshot-climate-startups

124 Flyvbjerg, B. & Gardner, D. (2023). *How Big Things Get Done* (Currency: New York) (pp. 43-59).

125 Flyvbjerg, B. (2021, November/December). Make Megaprojects More Modular (pp. 53-54). *Harvard Business Review*, 58-63 (highlighting Madrid's metro expansion, begun in 1995 and adding a total of more than 80 miles of rail and 76 stations in two phases of four years each; there, engineers relied on proven construction methods and a set modular designs for stations, while avoiding the temptation to add idiosyncratic flourishes of monumental architecture). https://hbr.org/2021/11/make-megaprojects-more-modular

126 Fialka, J. (2016, December 19). *Why China Is Dominating the Solar Industry.* E&E News (ClimateWire). https://www.scientificamerican.com/article/why-china-is-dominating-the-solar-industry

127 Gonzalez de Vicente, S., et al. (2022, May 30). Overview on the management of radioactive waste from fusion facilities: ITER, demonstration machines and power plants. *Nuclear Fusion*, 62, 1-20. https://doi.org/10.1088/1741-4326/ac62f7

128 Trembath, A., et al. (2012, May 23). *Where the Shale Gas Revolution Came from; Government's Role in the Development of Hydraulic Fracturing in Shale.* Breakthrough Institute. Retrieved October 7, 2022, from https://thebreakthrough.org/issues/energy/where-the-shale-gas-revolution-came-from

[129] Hart, D. (2017, July). *Across the "Second Valley of Death": Designing Successful Energy Demonstration Projects* (p. 5). Information Technology & Innovation Foundation (ITIF). https://www2.itif.org/2017-second-valley-of-death.pdf. Others have described the same distinction using different terms (e.g., "small device programmes" vs. "larger devices and installations"). *See* Hendry, C., Harborne P. & Brown, J. (2010, August). So what do innovating companies really get from publicly funded demonstration projects and trials? Innovation lessons from solar photovoltaics and wind (p. 4518). *Energy Policy*, 38(8), 4507-4519. https://doi.org/10.1016/j.enpol.2010.04.005

[130] Khatcherian, K. (2022, April). *Barriers to the Timely Deployment of Climate Infrastructure*. Prime Coalition. https://static1.squarespace.com/static/60903dcf05bc23197b2b993b/t/6269c7a70847634d26c0d81b/ 1651099594061/2022+Climate+Infrastructure+Full+Report_final

[131] Deutch, J. (2011). *The Crisis in Energy Policy* (Cambridge, Mass.: Harvard U. Press) (p. 117).

[132] See generally, Cohen, A., Goldthau, A. & Tagliapietra, S. (2023, August 17). *The Right Way to Intervene in Clean Tech*. Ejinsight (Hong Kong Economic Journal). https://www.ejinsight.com/eji/article/id/3537075/20230817-The-right-way-to-intervene-in-clean-tech

[133] Federal Trade Commission (FTC) (U.S.). (n.d.). *Spotlight on Trade Associations*. https://www.ftc.gov/tips-advice/competition-guidance/guide-antitrust-laws/dealings-competitors/spotlight-trade

[134] Rozansky, R. & Hart, D. (2020, May 18). *More and Better: Building and Managing a Federal Energy Demonstration Project Portfolio.* Information Technology & Innovation Foundation (ITIF). https://itif.org/publications/2020/ 05/18/more-and-better-building-and-managing-federal-energy-demonstration-project

[135] This tracks what MIT's John Deutch has proposed — creating a separate Energy Technology Corporation (ETC) to support large-scale demonstration projects. The ETC would be funded at the start by a large, one-time federal grant (a proposed $60 billion, dispensed over a decade), and then left largely to its own, technical devices. See Deutch, J. (2011, May). *An Energy Technology Corporation Will Improve the Federal Government's Efforts to Accelerate Energy Innovation*. The Hamilton Project, Brookings Institution, Discussion Paper 2011-05. Retrieved October 7, 2022, from https://www.hamiltonproject.org/assets/legacy/files/downloads_and_links/05_energy_corporation_deutch_paper_1.pdf

[136] Lester, R. & Hart, D. (2015, Winter). Closing the energy demonstration gap. *Issues in Science and Technology*, 31(2), 48-54. https://issues.org/closing-the-energy-demonstration-gap-2/

[137] Khatcherian, K. (2022, April). *Barriers to the Timely Deployment of Climate Infrastructure*. Prime Coalition. https://static1.squarespace.com/static/60903dcf05bc23197b2b993b/t/6269c7a70847634d26c0d81b/ 1651099594061/2022+Climate+Infrastructure+Full+Report_final

[138] See Nemet, G., Kraus, M. & Zipperer, V. (2016). *The Valley of Death, the Technology Pork Barrel, and Public Support for Large Demonstration Projects* (pp. 16, 22, 32). DIW Berlin, German Institute for Economic Research, Discussion Paper No. 1601, DIW Berlin 2016 ("[D]emonstrations are best seen as experiments, part of a process of continuous experimentation. Risk and failure are critical to learning." Yet "[o]nly 60% of the projects for which we could obtain motivation information [308 of 511 cases in 9 technology areas] stated something related to learning as an explicit objective."). https://ideas.repec.org/p/diw/diwwpp/dp1601.html. Paper published in August, 2018 in *Energy Policy*, 119(C), 154-167. https://doi.org/10.1016/j.enpol.2018.04.008

[139] Deutch, J. (2011, May). *An Energy Technology Corporation Will Improve the Federal Government's Efforts to Accelerate Energy Innovation*. The Hamilton Project, Brookings Institution, Discussion Paper 2011-05. Retrieved October 7, 2022, from https://www.hamiltonproject.org/assets/legacy/files/downloads_and_links/05_energy_corporation_deutch_paper_1.pdf

[140] It also requires that technical development up the S curve adhere to what one analysis calls a "coordinated sequential approach" — an element of a strategy that "seeks to identify lessons for the design, ordering and conduct of DTs in relation to the overall innovation process," one in which "learning should be paramount." Hendry, C., Harborne P. & Brown, J. (2010, August). So what do innovating companies really get from publicly funded demonstration projects and trials? Innovation lessons from solar photovoltaics and wind (p. 4518). *Energy Policy*, 38(8), 4507-4519. https://doi.org/10.1016/j.enpol.2010.04.005

[141] The Storing CO2 and Lowering Emissions (SCALE) Act is a bill (S. 799) introduced into the U.S. Senate on Mar. 17, 2021 by Sen. Christopher A. Coons, D-Delaware. It has 13 co-sponsors, 6 of whom are Republicans. For more information, see CATF (2021). *US CO_2 Transport and Storage Infrastructure: Climate Importance, Economic Opportunity, and Policy Need*. https://www.catf.us/wp-content/uploads/2021/03/CATF-SCALE-Act-Fact-Sheet-03.12.21.pdf

[142] Tachev, V. (2021, April 22). *Potential of Renewable Energy in Japan*. Energy Tracker Asia. https://energytracker.asia/potential-of-renewable-energy-in-japan/ (offshore wind in 2017 accounted for only 0.6% of that nation's energy use, however); Bardenhagen, Y. & Nakata, T. (2020, November 29). Regional spatial analysis of the offshore wind potential in Japan. *Energies*, 13(23), 6303. https://doi.org/10.3390/en13236303

[143] Larson, E., et al. (2021, October 29). *Net-Zero America: Potential Pathways, Infrastructure, and Impacts (final report)* (pp. 104-108) Princeton University, Princeton, N.J. https://netzeroamerica.princeton.edu/the-report

[144] For example, it has been argued that California's zero-emission vehicle (ZEV) mandate in the 1990s was premature; it stumbled due to its unrealistic timeline and massive scope. The better course would have been to introduce a new generation of batteries – as stationary technology – in the power sector, where they would (literally) have more room to advance while serving to stabilize the electricity grid, a relatively niche application.

[145] Lewis, M. (2020). *The Tees Valley — a hydrogen production hub* (presentation). Tees Valley Combined Authority. Retrieved October 7, 2022, from https://ukccsrc.hac.uk/wp-content/uploads/2020/07/Tees-Valley-16072020.pdf. An updated description of this initiative can be found here: Net Zero Teesside and NZT Power. Retrieved October 7, 2022, from https://www.netzeroteesside.co.uk/. The project, now known as Net Zero Teesside (NZT), is part of a cluster of projects on the east coast of the U.K. selected as priorities for the first phase of the government's carbon capture, usage and storage initiative. NZT's project proposal was backed by H2 Teesside, Kellas, Suez, CF Fertilizers, 8 Rivers, TVERF and BOC — all Teesside-based businesses. Key to the plan are (i) Net Zero Teesside Power (NZT Power), a fully integrated

860 MW combined cycle gas turbine electricity generating station with carbon capture, and (ii) the Northern Endurance Partnership (NEP), consisting of bp, Equinor, National Grid Ventures, Shell, and Total Energies, which will provide the common infrastructure needed to capture and transport CO_2 from carbon emitting projects, such as NZT Power, to secure offshore storage in the North Sea.

146 Hart, D. (2017, July). *Across the "Second Valley of Death": Designing Successful Energy Demonstration Projects* (pp. 9-10). Information Technology & Innovation Foundation (ITIF). https://www2.itif.org/2017-second-valley-of-death.pdf

147 The literature offers an impressive inventory of market-based ideas. A few examples: proposed California legislation SB 308, "Carbon Dioxide Removal Market Development Act." https://legiscan.com/CA/bill/SB308/2023; Rickeks, W., et al. (2022, November). Procure, bank, release: carbon removal certificate reserves to manage carbon prices on the path to net-zero. *Energy Research & Social Science*. https://doi.org/10.1016/j.erss.2022.102858; Lemoine, D. (2023, January). *Informationally Efficient Climate Policy: Designing Markets To Measure and Price Externalities*. National Bureau of Economic Research. (Working Paper No 30535). https://www.nber.org/system/files/working_papers/w30535/w30535.pdf

148 Geall, S. (2021, November 12). *The U.S.-China Climate Agreement Is Imperfect — But Reason To Hope*. The Guardian. https://www.theguardian.com/commentisfree/2021/nov/12/us-china-cop26-climate-carbon-superpower

149 Formed in 2010 following the U.N. Framework Convention on Climate Change Conference of Parties (COP 15) in Copenhagen in December 2009, the Clean Energy Ministerial (CEM) is a high-level global forum that promotes policies and programs to advance clean energy technology. The current 29 members of the CEM — 28 nations and the EU — account for 90% of the world's clean power and 80% of global clean energy investments, and the vast majority of public R&D in clean energy technologies. The forum operates through an annual high-level ministerial (the only regular meeting of energy ministers focused exclusively on clean energy), and year-round technical initiatives. Ministerial meetings rotate; the 13th was scheduled for Pittsburgh in Sep. 2022. CEM members — responsible for 83% of global GHGs — currently include Brazil, China, Germany, Japan, Mexico, Russia, the UAE, the U.K., and the U.S. CEM is coordinated by an independent multilateral Secretariat housed since 2016 within the International Energy Agency in Paris. See Clean Energy Ministerial. https://www.cleanenergyministerial.org