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Perspective
EXPERT INSIGHTS ON A TIMELY POLICY ISSUE

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Deep Decarbonization as a Risk Management Challenge

Deep decarbonization—reducing net human greenhouse gas emissions to zero by the second half of the 21st century—presents a daunting challenge.

Energy is vital to living standards and, at present, humanity relies on greenhouse gas–emitting fossil fuels for over 80 percent of its supply. As noted by many assessment reports, three billion people currently live in energy poverty, without electricity and relying on wood, dung, or other preindustrial fuels to cook and heat their homes (Clarke et al., 2014; Global Energy Assessment, 2012). Billions more, many of whom live in developed countries, have trouble affording the energy they do use. Buildings, factories, transportation systems, and other capital stock embody high-emitting technology and high-emitting behavior. Deep decarbonization will shift trillions of dollars from high- to low-emitting pathways, creating losers along with winners. Deep decarbonization will require radical changes in humanity's energy, transportation, and building sectors at a rate and scale without historical precedent.

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Yet a failure to achieve this goal of driving net human greenhouse gas emissions to zero presents serious risk to our climate, human society, and the environment.

Deep decarbonization requires bold action from technical, organizational, social, and political innovators. But such bold action brings its own risks. Innovators are often overconfident, seeing their path to the future as more certain than it might be; exaggerating their ability to forecast; and underestimating the impact of external factors on their chances of success, thus taking more risks than they realize. Innovators often suffer from the *silver bullet fallacy*—an undue focus on a single solution to a complex problem.

Overconfidence and the silver bullet fallacy may prove tolerable, sometimes even useful, for individuals and organizations. In his biography of Steve Jobs, Walter Isaacson describes how Apple's founder created a *reality distortion field* as part of proselytizing for previously unimagined products and services (Isaacson, 2011). Jobs ruined the lives of some of his employees, nearly went bankrupt, and was fired and rehired. But it is hard to argue that society did not benefit from his risk-taking. While deep decarbonization will require societal and technical change at least as transformational as the iMac and iPhone, society cannot accept the same risk of failure that Jobs took with his firm.

Innovators often suffer from the *silver bullet fallacy*—an undue focus on a single solution to a complex problem.

How, then, can society pursue a path to deep decarbonization that is both bold and careful?

The answer to this question begins by noting that deep decarbonization is a risk management challenge. *Risk* is sometimes defined as the likelihood of an event's occurrence multiplied by a measure of the event's consequences, good or bad. But with deep decarbonization, we seldom know the probabilities—or sometimes even the consequences—with any confidence. In addition, people often value the same consequences differently. With deep decarbonization, risk is usefully defined more broadly as "the potential for adverse consequences when something of value is at stake, and the outcome is uncertain" (Jones et al., 2014, p. 199).

Three concepts have proven particularly important to understanding the full dimensions of deep decarbonization as risk management. These are

- risk governance
- complexity
- robustness.

We have developed this Perspective to introduce these three concepts. This Perspective contains three short briefs. Each brief describes one concept and is intended for audiences committed to deep decarbonization but unsure of how best to achieve it. These briefs do not provide policy recommendations. Rather, they aim to help those interested in realizing deep decarbonization to incorporate a broad view of risk into their thinking.

The first brief introduces *risk governance*. This concept helps move the discussion beyond identifying promising

Key Takeaways

- Risk governance provides a useful framework for organizing thinking and acting in pursuit of deep decarbonization because it applies the principles of governance—the processes, traditions, and institutions by which authority is exercised and decisions are taken and implemented—to the identification, assessment, management, and communication of risks in a diverse and decentralized society. Risk governance includes the totality of actors, rules, conventions, processes, and mechanisms concerned with how relevant risk information is collected, analyzed, and communicated and how and by whom risk management decisions are taken.
- Decarbonization presents a complex challenge, rather than a complicated one. Complex systems consist of many elements interacting in ever-shifting, often disordered ways. Complex systems often respond nonlinearly to small perturbations, and their overall behavior can be understood but not predicted. Managing a complex system is fundamentally different than managing a complicated one and often offers more opportunities for small interventions to result in significant change.
- Robustness provides a useful concept for managing the complexity of the decarbonization challenge. Seeking robust strategies involves considering a multiplicity of plausible futures, evaluating how strategies perform over a wide range of such futures, and often employing adaptive pathways that adjust over time to perform well over many futures.

decarbonization pathways to asking the broader question of how a diverse society with no central authority can successfully pursue such an ambitious goal. Risks associated with any deep decarbonization pathway include potential failure to achieve sufficiently low levels of net emissions and potential adverse side effects—for example, habitat destruction from widespread deployment of renewable energy sources or nuclear power accidents.

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The second brief discusses the complexity of the decarbonization challenge. It highlights the important differences between complicated and complex problems and emphasizes the importance of developing a "complexity mindset" for considering the path forward on decarbonization.

The third brief introduces robustness as an especially promising concept for managing the decarbonization challenge, particularly given its complexity and that complexity's inherent uncertainty. Successful risk governance requires robustness. In addition to its importance for addressing uncertainty, robustness can help facilitate processes that transcend traditional boundaries between government, industry, academia, and civil society globally.

This brief concludes with a simple illustration of the benefit of pursuing robust adaptive decarbonization pathways.

Brief 1: Risk Governance as a Framework for Leadership on Decarbonization

The Need for Risk Governance

As noted by Ortwin Renn in his classic book *Risk Governance*, risk—the uncertain potential for adverse side effects—often arises as humans pursue their aspirations, wants, and needs (Renn, 2008). Climate change offers an archetypal example. The fossil fuel–powered economic growth that has helped create opportunities for billons of people to live more fulfilling lives is also warming the earth and changing its climate.

Risk governance provides a framework for considering how a vast, decentralized, and diverse society can best pursue deep decarbonization while continuing to expand opportunities and avoiding the many adverse consequences that may accompany large societal transformations. Risk governance helps to frame questions: What actions, processes, traditions, and institutions can best reduce risk? By whose authority should which actions be taken and in whose interests? What are the cognitive, social, technical, financial, institutional, and other barriers that impede appropriate action? The understanding and practice of risk governance draws on and applies to many fields and many types of risks. But the challenges can prove particularly acute when facing what the International Risk Governance Council (IRGC) calls slow-developing catastrophic risks, like climate change.

One of the critical observations of risk governance is that, in an increasingly globalized and technologically disruptive world, traditional forms of governance lack global authority and adapt and evolve more slowly than the pace of social change. Effectively managing many risks requires what Elinor Ostrom (1990) called polycentric governance: the engagement of multiple actors, in particular stakeholders beyond governments, often using mechanisms beyond the traditional tools of public policy.

We present the IRGC's Risk Governance Framework as a means of spurring discussion about the need and potential for new arrangements for effective governance of decarbonization. Rather than attempting to propose any particular prescription for action, we introduce the framework to help facilitate discussion among stakeholders about the appropriate means of decarbonization. To spur such discussion, this brief concludes with an illustrative partial assessment of risk governance deficits that might inhibit the pursuit of deep decarbonization goals.

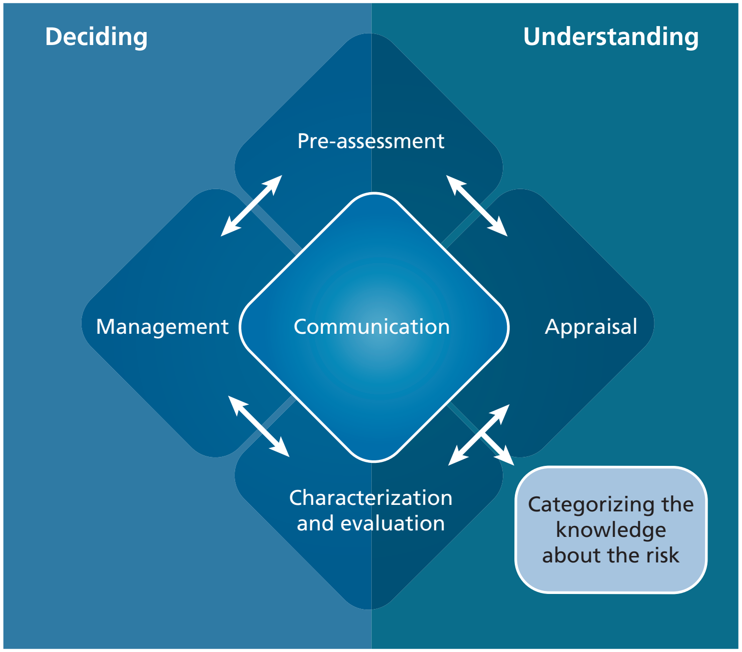
IRGC Risk Governance Framework

Consistent with Renn (2008), the IRGC's framework identifies five elements of risk governance. As shown in Figure 1, the following are the elements in the framework:

- *Pre-assessment* involves relevant actors and stakeholder groups in defining various perspectives regarding the risks, identifying associated opportunities, and designing strategies for addressing these risks.
- *Appraisal* gathers the scientific evidence relevant to each risk, including the physical and socioeconomic

FIGURE 1

IRGC Risk Governance Framework



SOURCE: IRGC, 2006.

components, and identifies the uncertainties involved.

- *Characterization and evaluation* determines the need for risk reduction actions by applying societal values and norms to judgments regarding the tolerability and acceptability of various risks.
- *Management* identifies, evaluates, selects, and implements appropriate actions to reduce risks.
- *Communication* entails a two-way learning process among information users and producers that builds trust and helps decisionmakers and the public to take risk management actions consistent with both scientific evidence and society's diverse values.

It is useful to organize these five elements into the two broad categories of understanding risks and deciding on approaches for managing them, as shown in Figure 1. These categories inform the discussion of risk governance deficits later in this brief and the implications of complexity in the next brief.

Risk governance includes these five elements as an ongoing cycle that typically moves from pre-assessment, to appraisal, to characterization, to management, and then returns to evaluation and reassessment. These cycles emphasize the need for ongoing, iterative management of complex risks. Rather than seeking linear and static solutions, iterative risk management is characterized by flexibility, continuous improvement, and regular updating based on new information and understanding.

Risk governance also emphasizes the centrality of communication in both understanding and acting on risks—in particular, the importance of communicating the need and potential methods for pursuing deep decarbonization.

Risk Governance for Deep Decarbonization

The next two briefs will introduce the concepts of complexity and robustness. The risk governance framework can help integrate these themes into an overarching process for understanding and acting in pursuit of deep decarbonization, as detailed in the following list:

- *Pre-assessment* emphasizes that deep decarbonization requires pursuing multiple pathways simultaneously because no single pathway can guarantee success. In addition, this element emphasizes the importance of a "complexity mindset" because decarbonization involves complex systems, not complicated ones.
- *Appraisal* supports the gathering of scientific information relevant to each of the many pathways, including information relevant to unexpected opportunities, potential failures, and the numerous impacts and co-benefits that the pathway might entail for different subsets and individuals in society.
- *Characterization and evaluation* supports identification and evaluation of the policies and investments required for each of the various pathways, how those pathways create and restrict future options and future progress toward decarbonization, how unwanted impacts might be controlled and co-benefits encouraged, and the trade-offs between various sets of policies and investments as seen by different subsets and individuals in society.
- *Risk management* requires operating in a complex (rather than complicated) environment—in particular, sensing and responding, tolerating failure, and recognizing and responding to emerging patterns. This element also requires operating in a polycentric environment with many diverse centers of power.
- *Communication* requires that the many parties taking part in the decarbonization endeavor make known their interests and understanding of risk: those taking risk management actions make clear the rationale for those actions, and all parties engage with the concepts of complexity and robustness that seem central to the successful pursuit of deep decarbonization.

Avoiding Risk Governance Deficits

To help avoid risk governance failures, the IRGC recommends looking for deficits at each stage of the process. Figure 2 identifies 20 potential types of deficits, organized

FIGURE 2

Potential Deficits That Can Occur in Each of Two Broad Categories of the Risk Governance Process

Cluster A: Assessing and understanding risks

Gathering and interpreting knowledge

A1: Missing, ignoring, or exaggerating early signals of risk

A2: Lack of adequate knowledge about a hazard, including probabilities and consequences

A3: Lack of adequate knowledge about values, beliefs, and interests, and therefore about how risks are perceived by stakeholders

Dealing with disputed, potentially biased, or subjective knowledge

A4: Failure to adequately identify and involve relevant stakeholders in risk assessment

A5: Failure to consider variables that influence risk appetite and risk acceptance

A6: The provision of biased, selective, or incomplete information

Dealing with knowledge related to systems and their complexity

A7: Lack of appreciation or understanding of the potentially multiple dimensions of a risk

A8: Failure to reassess in a timely manner fast and/or fundamental changes occuring in risk systems

A9: Over- or underreliance on models

Acknowledging that knowledge and understanding are never complete or adequate

A10: Failure to overcome cognitive barriers to imagining events outside of accepted paradigms

Cluster B: Managing risks

Preparing and deciding on risk management strategies and policies

B2: Failure to design risk management strategies that adequately balance alternatives

B3: Failure to consider a reasonable range of risk management options

B4: Inappropriate balancing of benefits and costs in an efficient and equitable manner

B6: Failure to anticipate, monitor, and react to the outcomes of risk management decisions

B7: Inability to reconcile the time frame of the risk with those of decisionmaking and incentive schemes

B8: Failure to balance transparency and confidentiality

Formulating responses, resolving conflicts, and deciding to act

B1: Failure of managers to respond to early signals that a risk is emerging

B11: Lack of understanding of the complex nature of commons problems and of adequate management tools

B12: Inappropriate management of conflicts of interests, beliefs, values, and ideologies

B13: Insufficient flexibility in the face of unexpected risk situations

Developing organizational capacities for responding and monitoring

B5: Failure to muster the necessary will and resources to implement risk management policies and decisions

B9: Failure to build or maintain an adequate organizational capacity to manage risk

B10: Failure of the multiple departments or organizations responsible for a risk's management to act cohesively

SOURCE: IRGC, 2010.

into the broad categories of understanding and assessing risks, and acting and managing risks.

To illustrate the value of this deficit checklist, we note several deficit types of particular importance to deep decarbonization:

- Deficits A7, A8, and A9 draw attention to potentially inadequate knowledge and appreciation of system complexity, an overreliance on "predict, then act" planning, failure to recognize when fundamental changes occur in the system, and a misuse of models that might provide a false sense of precision for some questions (while completely ignoring others).
- Deficits B6 and B13 focus on potential shortcomings in the ability to anticipate, monitor, and respond to the results of policy interventions. These shortcomings may prove particularly salient given the virtual certainty of surprises in climate change and the process of decarbonization.
- Deficit B9 focuses on a potential lack of institutional capacity to pursue robust strategies within complex systems.

As these examples suggest, risk governance provides a useful framework for organizing, thinking, and acting in pursuit of deep decarbonization.

Brief 2: Decarbonization: A Problem Requiring a "Complexity Mindset"

Solutions to climate change are often characterized by simple narratives, such as using renewables to decarbonize. Simple narratives can prove compelling, and renewable energy sources will unquestionably prove a critical component of decarbonization. Nonetheless, renewables alone are insufficient to reduce net human greenhouse gas emissions to zero. Deep decarbonization also requires transitions in most economic sectors and most regions of the world, ranging from the ways in which people grow and transport their food to the ways in which they build their cities, work, and commute to their jobs. Transitions in all the components of this complicated web are necessary to reduce net human greenhouse gas emissions to zero by the second half of the 21st century.

But decarbonization goes beyond being a complicated challenge with many interconnected parts. Rather, deep decarbonization presents an archetypal *complex* challenge. This distinction between complicated and complex is important. In *It's Not Complicated: The Art and Science of Complexity for Business*, Rick Nason noted that "[b]efore anything can be managed, it must be recognized for what it is. This is especially important for complex versus complicated systems" (Nason, 2017, p. 107).

Simple systems—such as a pendulum—have cause-and-effect relationships that are easy to understand. *Complicated* systems—such as a jet airplane—are collections of simple systems interacting with each other through ordered, stable relationships. The behavior of a complicated system may not be immediately obvious. But because the behavior of each system component can be understood independently from the others, the overall system is ultimately understandable, predictable, and contained within fixed bounds.

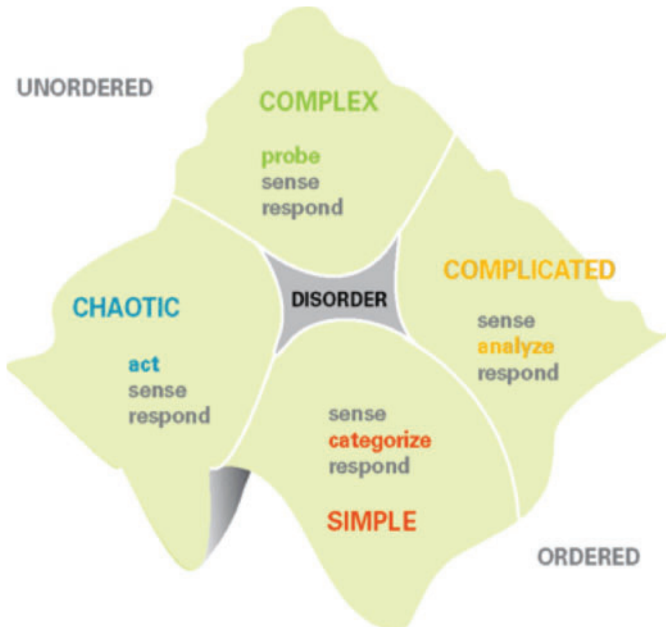
In contrast, a *complex* system—such as a community of people—is a collection of many elements interacting in an ever-shifting, often disordered way. The behavior of any one element in a complex system cannot be understood independently, only in the context of ever-changing interactions with other elements. A complex system thus exhibits nonlinear behavior and a property called *emergence*: a tendency to organize itself into one of several possible novel and coherent states and, in some cases, to jump suddenly between those states. Because seemingly random factors can send a complex system along a pathway that leads to one *particular* state rather than another *possible* state, the behavior of such a system can be understood but not predicted.

Managing a complex system is fundamentally different than managing a complicated one, as summarized by Nason (2017) using the Cynefin framework (a commonly-used framework for decisionmaking) in Figure 3. With a complicated system, we seek to predict and then control its behavior. With a complex system, we seek to understand the internal logic of its contingent pathways, probe to understand its current state, and respond to what we learn. As Nason (2017) noted, managing a complex system in many ways proves more challenging than managing a complicated one, but it also offers more opportunities because small interventions can sometimes make large differences in the state that emerges.

Decarbonization as a Complex Challenge

Every sector of the global economy and every region of the world contribute to greenhouse emissions. The socioeconomic systems relevant to decarbonization are thus composed of a vast number of components. Much of the emission reduction narrative focuses on the electric sector, which contributes only 40 percent of the world's emissions. Transportation, industry, buildings, agriculture, and land use contribute much of the rest. In any scenario, deep decarbonization requires transformation of sectors other than energy. At one extreme, deep decarbonization could entail decarbonizing electricity production while contributing to the electrification of most of the rest of the economy. At the other extreme, decarbonization might entail much less electrification and directly decarbonizing other sectors, including the improvement of strategies for removing carbon from the atmosphere.

FIGURE 3
Cynefin Framework Showing Management Approaches Needed for Different Types of Systems



Similarly, much discussion of the promise of decarbonization through electricity generation focuses on advanced industrial economies, such as the United States and Europe. But less than one-third of current carbon dioxide emissions stem from these economies. While the average American emits two times more carbon dioxide than the average Chinese person, and ten times more than the average Indian, the United States' total emissions as a country are now falling, and those of India and China are growing quickly, with China now emitting more carbon dioxide than the United States and the European Union combined.

However, decarbonization needs to focus not only on eliminating emissions from the existing electricity generation capacity in advanced industrialized economies—which have grown rich on decades of emissions that still reside in our atmosphere—but also on solutions that can satisfy the dramatically increasing energy demand in parts of the world where expanded electricity generation is critical to social progress.

These components, which are diverse both in terms of geographic and sectoral characteristics, interact with each other through a dense web of connections. For example, expanding vehicle electrification can reduce or increase emissions, depending on whether the electric power for charging comes from renewables or coal-fired plants. In addition, adding large numbers of electric vehicles to the grid can add demand at times when the grid can least handle it, exacerbating intermittency challenges. Expanding crops for biofuels can raise food prices, exacerbating inequality. Conversely, the advent of inexpensive battery technology would start a cascade of beneficial changes, revolutionizing the production and distribution of electricity.

> Decarbonization would be complex even if the simple systems at its core were well understood.

Decarbonization would be complex even if the simple systems at its core were well understood. But uncertainty only amplifies the complexity. Decarbonization involves deep technological uncertainty. Realizing the transformation of global electricity generation alone would require technology, cost, and performance improvements that, while certainly possible, are far from assured. Such improvements include the deployment of clean energy technologies at a scale as of yet unprecedented, advancement in technologies for the storage of intermittently generated electricity, and progress in transmission of electricity generated by dispersed technologies. In addition, these technologies are embedded in complex socioeconomic systems. The evolution of everything from oil prices to electoral politics to behavioral norms will affect and be affected by decarbonization in profound and uncertain ways.

In addition to the socioeconomic systems related to decarbonization, the climate system itself is complex. Each of its many components, while individually understandable, interact with other components across many different spatial and temporal scales. Such feedback dominates the behavior of the climate system as we now know it. Descending ocean waters in the North Atlantic drive the Gulf Stream, which flows from the equator and keeps Europe at a much warmer temperature than Alaska, despite being at the same latitude. Decadal oscillations in the temperature of the Pacific Ocean's surface near China drive El Niño patterns of drought in California. The global carbon dioxide concentration changes as plants in the Northern Hemisphere come alive in the spring and then die off in the fall.

As increasing greenhouse gases in the atmosphere trap more heat, new patterns may emerge. Ice and snow in northern latitudes reflect sunlight, which helps cool the earth, but as global temperatures increase, this ice melts, and forests cover the tundra. Ice-free Arctic waters and new forests are already absorbing more light and heat, accelerating the rise in the earth's temperature. In addition, Arctic tundra contains vast deposits of methane, one of the most potent greenhouse gases. Melting tundra may release vast amounts of methane, significantly increasing warming and creating a self-reinforcing cycle of heating. Greenland's and Antarctica's miles-thick ice sheets melt slowly, but as they begin to melt, they also crack, which accelerates the slide of the ice sheets into the sea.

The U.S. National Climate Assessment's recent *Climate Science Special Report* described two types of surprises, both related to complexity (Wuebbles et al., 2017). The first type of surprise is a *compound event*, where multiple extreme events occur simultaneously or sequentially, such as two hurricanes striking the same area in the same season, which creates a larger impact than the sum of multiple events. The second is a *critical threshold* or *tipping point*, such as the temperature at which the rapid fracturing of ice sheets becomes irreversible, beyond which impacts become discontinuously larger. In particular, passing such a tipping point could "even shift the Earth's climate system, in part or in whole, into new states that are very different from those experienced in the recent past" (Wuebbles et al., 2017, p. 33).

Implications for Understanding

Complex systems call for different ways of understanding the world.

In his book, Nason encouraged a "complexity mindset," which accepts that complex systems exist and need to be dealt with in a different way than complicated systems; understands that there are certain limitations on the extent to which complex systems can be controlled; and, perhaps most importantly, embraces the constraints *and opportunities* that arise when dealing with complexity. We would like to highlight this latter dimension, which Nason characterized as "a creative mindset [that] focuses on what can be, rather than what is" (Nason, 2017, p. 144).

Many commentators have noted that an often-venerated approach to science, called *reductionism*, does not work for complex systems. Reductive science, ideal for complicated systems, involves dividing a system into its component parts, understanding each part individually, and then aggregating these understandings to understand the whole. The philosopher of science Sandra Mitchell suggests instead to use an approach that she calls *integrative pluralism*, which accepts the relevance of multiple explanations and models as well as the evolving, contextual nature of knowledge in place of a static universalism (Mitchell, Decarbonization efforts, rather than focusing on a single "best guess" course of action, should actively probe multiple possible pathways.

2009).[1] As is common among discussions of complexity, Mitchell draws on examples from biology and evolution and notes that life on today's earth has logic and structure. But it also includes improbable creatures, such as flamingos and humans. If we were to rerun the development of life on earth from the beginning of multicellular life, the many contingencies and branch points along the way make it highly unlikely that we would see the same creatures or even broad categories of creatures (e.g., mammals, birds, flowering plants) emerge.

Such contingency also characterizes past and future pathways relevant to decarbonization. Just because humans have created energy and transportation systems whose logic and structure have remained relatively stable for many decades does not mean that such systems will retain the same logic and structure over the next century. Whatever path these systems follow into the future will have a compelling logic, but our current scientific understanding of these potential paths should encompass the possibility that there may exist different pathways with different logic.

Implications for Acting

Complex systems call for different ways of acting in the world.

Nason (2017) argued that complex systems require what he called *pattern-based management*. With complicated systems, we can gather data, analyze the system's behavior, and use this information to choose a response that will generate desired and predictable outcomes. Complex systems, in contrast, can lack an obvious or stable relationship between cause and effect. But we can probe the systems, sense emerging patterns, act to reinforce favorable patterns and to suppress unfavorable ones, and then probe again.

Recognizing the complexity of the climate system emphasizes the logic of pursuing deep decarbonization through such pattern-based management. Despite efforts at reducing uncertainty, it remains unlikely that scientists will be able to exclude the possibility of the worst-case scenarios of the climate change impact distribution (Wagner and Weitzman, 2015). Benefit-cost frameworks, while providing useful information, cannot definitely determine an appropriate decarbonization rate or goal. In addition, we should also not be surprised if we lack any actionable

[1] Mitchell draws on images from Stephen Jay Gould's classic book *Wonderful Life* (1990), which describes the birth of multicellular life in the Cambrian Explosion six hundred million years ago, the contingency of the pathways that subsequently led to the world we now inhabit, and how biologists for a century misinterpreted the ample fossil evidence so as to avoid the need to confront that contingency.

warning from the climate system that can help guide our decarbonization effort. For instance, analysis of warning times suggests that by the time we observe the beginnings of a large-scale collapse of the Antarctic ice sheets, it will be too late to halt it, even with fast-acting solar radiation management geoengineering (Wong, Bakker, and Keller, 2017). This suggests that decarbonization efforts, rather than focusing on a single "best guess" course of action, should actively probe multiple possible pathways.

In their work on what they called "super-wicked problems," Levin and colleagues (2012) noted decarbonization's political and moral challenges—in particular, the lack of any effective central authority, broadly shared responsibility for creating the problem, and unequal distribution of benefits and costs across different places and generations. In response, Levin and colleagues suggested exploiting the path dependency inherent in the complex socioeconomic systems related to decarbonization (Levin et al., 2012). They called for an applied forward reasoning that simulates the effects of alternative responses looking for near-term actions that can "constrain our future selves (Levin et al., 2012, p. 129)." Such responses might include "sticky" interventions designed to entrench support over time while expanding the populations they cover. Echoing Nason and Mitchell on adopting a complexity mindset, Levin and colleagues (2012) suggested exploiting the opportunity inherent in the emergent behavior of complex systems by fostering feedback that helps our energy, transportation, building, agricultural, and other systems reorganize themselves into a novel, coherent, and low-carbon state.

Brief 3: Robustness as an Approach for Managing Decarbonization Risk

How, then, to pursue deep decarbonization in the face of this complexity and the correspondent uncertainty? As Nason (2017) suggested, it is critical to develop a complexity mindset, one which

- accepts that complexity exists
- accepts that complex systems need to be managed differently than complicated systems
- accepts that there are certain limitations on what can be controlled in addressing these challenges
- embraces both the constraints and opportunities that come with dealing with complexity.

Thinking in terms of the *robustness* of decarbonization strategies can help implement these ideas. In particular, the concept of robustness can help balance the constraints and opportunities posed by decarbonization and can help us to think effectively about what can be rather than what is.

Robustness and resilience stand in contrast to what we might call "predict, then act" thinking. To make informed choices, decisionmakers often seek predictions about the future. But the quest for predictions can prove counterproductive, fostering overconfidence, discord, and narrow thinking. President Dwight Eisenhower reportedly remarked, "if a problem cannot be solved, enlarge it." "Predict, then act" thinking encourages us to reduce uncertainty by narrowing our focus, prioritizing the questions that we think are most amenable to prediction.

In contrast, seeking robust strategies encourages more expansive thinking over potential futures and strategies. Robustness encourages an iterative process of stress-testing

There exist many ways to define robustness. But for a transformational, multifaceted challenge like deep decarbonization, it proves useful to think in terms of *regret*.

action plans against a wide range of futures, seeking to understand potential vulnerabilities and missed opportunities. This often encourages deliberation and discussion on the best steps forward.

As noted in the book *Shaping the Next One Hundred Years*, seeking robust strategies involves three key elements, each resonant with a complexity mindset (Lempert, Popper, and Bankes, 2003).

Consider a multiplicity of plausible futures. When pursuing a transformational challenge, any single best estimate of the path toward our goals is sure to be wrong on many important details. Explicitly considering a diverse set of alternative futures can alert us to important dangers and opportunities that we might have missed, even if we cannot know which future will eventually unfold. Robustness adopts this key concept from scenario thinking and then explicitly chooses multiple futures to serve two purposes: (1) to stress-test our plans to best identify how they might fail and explore for missed opportunities and (2) to enhance buy-in among diverse groups by including scenarios that correspond to each of their competing worldviews. Considering such scenarios also helps make our assumptions transparent, enhancing engagement with a broad range of stakeholders and increasing the likelihood that our ultimate plan will meet our goals.

Seek robust strategies, rather than optimal ones. “Predict, then act” thinking encourages us to search for a single best strategy. But prediction-based strategies often prove brittle, failing when the future turns out differently than expected. Such prediction-based strategies also prove contentious because different stakeholders often hold very different views on what constitutes *best*. Robust strategies aim to perform well over a wide range of plausible futures, so that they succeed even when the future inevitably surprises us. Robust strategies also pursue multiple objectives, both respecting the heterogeneity of opinion that is a fundamental (and desirable) characteristic of our world and enhancing the legitimacy of the planning process by making proposed trade-offs among objectives transparent to all concerned.

There exist many ways to define robustness. But for a transformational, multifaceted challenge like deep decarbonization, it proves useful to think in terms of *regret*. Decision scientists define a strategy’s regret as its distance from the best one could do if one knew the future perfectly. Robust strategies seek low regret over most if not all plausible futures.

Follow adaptive pathways to achieve robustness. Decarbonization pathways are often portrayed as fixed plans, unfolding as a series of well-choreographed events over several decades. In contrast, robust strategies are often designed to be flexible, evolving over time in response to new information.

To craft such robust adaptive pathways, we can usefully think in terms of near-term actions, signposts to monitor, and contingency actions. *Near-term actions* are what we do today. Such actions often seek to shape the future—for instance, by investing in promising new technologies and setting ambitious goals to motivate action. Near-term actions also seek to keep options open because we do not know which of many plausible paths will best lead to our objectives. *Signposts* represent the most promising trends and indicators to monitor that will help us identify when it becomes advantageous to adjust course, such as shifting investment from one set of technologies to another. *Contingency actions* represent the specific actions that constitute the course adjustments we would take in the future as we learn more. Contingency actions are important because one cannot reasonably choose near-term actions and signposts without thinking through the multiple pathways down which they might lead:

> Complicated thinkers tend to get too intellectually invested in an idea and refuse to let go, despite sometimes overwhelming evidence that the plan is not working. Complexity thinkers have the humility and flexibility not to get trapped into this low-probability strategy. (Nason, 2017)

In addition to identifying strategies less vulnerable to surprise, robust thinking can also help build consensus in contentious political environments. The philosopher John Rawls called for a "political, not metaphysical" approach to agreement among parties with diverse expectations and interests (Shapiro, 2003). Echoing political thinkers from antiquity to the present, Rawls argued that people might more easily reach consensus on specific actions to undertake rather than on the general principles, comprehensive doctrines, or metaphysical commitments that might lead one to support those actions. "Predict, then act" approaches begin with the metaphysical ambition of universal agreement on a particular (probabilistic) best estimate of the future. In their article for *Scientific American*, Popper, Lempert, and Bankes (2005) show how, in contrast, robust thinking seeks consensus on near-term actions consistent with different visions of the future.

To illustrate these concepts, consider a very stylized example with only two alternative strategic bets one could make to decarbonize the electricity sector by 2050. One strategy, All Renewables, would invest only in renewables. If successful, this strategy would decarbonize all electricity generation by 2050 and transform the economy to a more sustainable, all–renewable energy system. The other strategy, Diverse Technologies, would invest in a diverse set of carbon-free electric generation technologies, including renewables, carbon capture and storage, and advanced nuclear energy. If successful, this strategy would also decarbonize all electricity generation by 2050, but not necessarily with an all–renewable energy mix.

Each strategy makes assumptions about the future. The All Renewables strategy assumes that positive feedback in this complex system can prove decisive. Directing all efforts toward renewables would give these technologies an increasing share of investment, enhance economies of scale, and favorably shape the policy landscape and expectations, thus speeding the transition to an all-renewable energy future. The Diverse Technologies strategy assumes that no single technology is guaranteed to fully decarbonize the electric sector by 2050, even if all efforts are devoted to that technology. Thus, spreading investment and interest among many options would make decarbonization most likely.

Table 1 examines the robustness of these two strategies using what van Asselt and Rotmans (1996) first called a "utopia-dystopia" matrix. The rows show the two strategies. One column shows a future consistent with the assumptions of the All Renewables strategy—one in which a renewables transformation is possible if we pursue it with enough vigor. Another column shows a future consistent with the assumptions of the Diverse Technologies strategy—one in which renewables cannot fully decarbonize the electric sector, but a diverse portfolio of technologies can.

The colors of the cells show the regret for each strategy in each future. Green cells show the best possible outcomes that result from following a strategy in a future consistent with its assumptions. By 2050, the All Renewables strategy results in a sustainable, all–renewable, decarbonized electric sector in the Renewables Transformation Possible future, while the Diverse Technologies strategy results in a decarbonized electric sector in the Renewables Transformation Not Possible future. The strategies fare less well in the futures inconsistent with their assumptions, as indicated by the yellow and red cells. In the Renewables Transformation Possible future, the Diverse Technologies strategy proves more costly than necessary and results in a less sustainable electric sector. The strategy may or may not decarbonize the electric sector, depending on the importance of positive feedback focused on a single technology. In the Renewables Transformation Not Possible future, the

TABLE 1

Utopia-Dystopia Matrix for Notional Decarbonization Pathways to 2050

Strategy	Renewables Transformation Possible	Renewables Transformation Not Possible
Predict, then act		
All Renewables	Achieve deep decarbonization (+) Renewables transformation	Fail to achieve deep decarbonization
Diverse Technologies (Predicted diversity)	Achieve deep decarbonization (––) Higher than necessary cost (––) Fewer renewables than possible	Achieve deep decarbonization
Robust		
Renewables First (Flexibility with signposts)	Achieve deep decarbonization (+) Renewables transformation (–) Slightly higher cost	Achieve deep decarbonization (–) Slightly higher cost

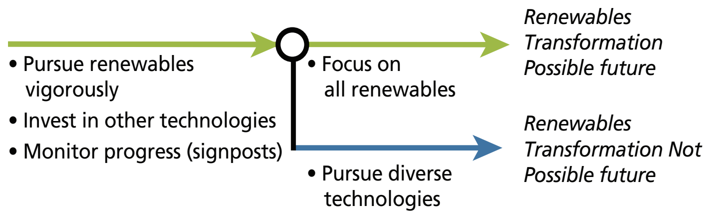
NOTE: This matrix shows outcomes of alternative decarbonization strategies in futures consistent and not consistent with the strategies' assumptions. Green, yellow, and red cells indicate low, medium, and high regret, respectively. (+) indicates achievement of a goal important to many stakeholders. (––) indicates failure to achieve a goal important to many stakeholders. (–) indicates slightly missing a goal important to many stakeholders.

All Renewables strategy may fail to decarbonize the electric sector by 2050.

If we could predict the future with confidence, the choice of strategy would be obvious. But predicting and acting erroneously has high regret. Fortunately, information about each strategy's potential vulnerabilities suggests a potentially more robust alternative. We might pursue a Renewables First strategy, configured as an adaptive pathway and shown in Figure 4. The strategy would begin by vigorously pursuing renewables, but with additional investments in other technologies. Signposts would monitor progress across all technologies and, as it became clear which future we inhabit, the strategy would adjust to an all–renewable or a more diverse path. Such a strategy would prove a bit more expensive than acting on a perfect prediction. But, if properly executed, the robust strategy would have low regret in both futures.

Such robust thinking can prove broadly useful in managing the challenges of deep decarbonization. For instance, there are numerous integrated assessment simulation models currently used to chart out best-estimate decarbonization pathways in support of "predict, then act" analysis. Such analyses often include numerous technology options, such as the carbon wedges—sets of technology options that each provide a fraction of the desired emission reductions—introduced by Pacala and Socolow (2004). New information technology now makes it possible to use these models for a different purpose, placing them on cloud-based or cluster computers and stress-testing robust and flexible adaptive pathways over thousands or millions of plausible paths in the future. Machine learning and computer visualization then help develop informative visualizations from these runs, which can help decisionmakers work with one another to craft robust and flexible plans.

FIGURE 4
Potential Robust Adaptive Decarbonization Pathway



Robust thinking, supported by cloud or cluster-based multi-scenario analysis, is increasingly used by organizations such as the U.S. Bureau of Reclamation (U.S. Department of the Interior, Bureau of Reclamation, 2012) and the World Bank (Cervigni et al., 2015; Ray and Brown, 2015) to adapt to the impacts of climate change. Such analyses have more recently been introduced into the study of decarbonization. Recent work used an ensemble of 40,000 runs of one of the integrated assessment models used to craft the latest generation of Intergovernmental Panel on Climate Change (IPCC) scenarios to suggest important, policy-relevant scenarios unexamined by the IPCC (Lamontagne et al., 2018). Another recent study used millions of runs of an agent-based complexity model to identify robust "sticky" policies (Isley et al., 2015).

Whether supported by quantitative analysis or qualitative thinking, seeking robust strategies helps shift attention from the prediction-based question "What will happen?" to a complexity mindset that asks, "How do we shape a complex, hard to predict, and transformative future more to our liking?"

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About the Decarbonization Dialogues

The material in this Perspective was written to support the Decarbonization Dialogues, a series of workshops organized by the Frederick S. Pardee Center for Longer Range Global Policy and the Future Human Condition. The most recent workshop, "Dialogue on Deep Decarbonization," was held at the offices of Generation Investment Management in San Francisco, California, on April 5, 2018, and the briefs in this Perspective were shared there. Attendees included representatives of the following organizations: Alphabet/Nest Labs, Arizona State University, the Laura and John Arnold Foundation, Bank of America, Capula Investment Management, the Carlyle Group, the Carnegie Climate Geoengineering Governance Initiative, Center for Carbon Removal, Children's Investment Fund Foundation, Clean Air Task Force, ClimateWorks Foundation, Emerson Collective, Generation Investment Management, the William and Flora Hewlett Foundation, Interface, Lawrence Livermore National Laboratory, the Mitchell Foundation, Morrison Foerster LLP, NearZero, the NorthBridge Group, the David and Lucile Packard Foundation, Radicle Impact, Bernand and Anne Spitzer Charitable Trust, Stanford University, The Nature Conservancy, TomKat Foundation, and the University of California, Berkeley.

About This Perspective

The international community acknowledged in the 2015 Paris Agreement—for the first time—that halting climate change at an acceptable level would require net human emissions of greenhouse gases to approach zero in the second half of this century. Many national governments, international organizations, businesses, cities, philanthropies, and nongovernmental organizations are now pursuing activities aimed at such deep decarbonization. But study after study makes it clear that the current scale and scope of decarbonization efforts are insufficient to cap the dangerous risks of climate change.

The Frederick S. Pardee Center for Longer Range Global Policy and the Future Human Condition (Pardee Center) is partnering with other research organizations, nonprofits, philanthropies, and businesses to better understand the global challenge of deep decarbonization. In particular, the Pardee Center aims to increase awareness of deep decarbonization as a risk management challenge. Funded by the Metanoia Fund, the Pardee Center has organized two workshops as part of a series called the Decarbonization Dialogues. The most recent workshop, "Dialogue on Deep Decarbonization in the Face of Risk and Uncertainty," was held at the offices of Generation Investment Management in San Francisco, California, on April 5, 2018.

As part of the preparatory materials for the workshop, the Pardee Center produced a set of short briefs framing deep decarbonization as a risk management challenge, focusing on the concepts of risk governance, complexity, and robustness. This Perspective makes revised versions of those briefs available to a broader audience.

This Perspective should be of interest to those interested in the challenge of deep decarbonization and in the themes of risk governance, complexity, and robustness as applied to difficult challenges of public policy.

About the RAND Frederick S. Pardee Center for Longer Range Global Policy and the Future Human Condition

The Pardee Center, part of RAND Innovation, aims to enhance the overall future quality and condition of human life by aggressively disseminating and applying new methods for long-term policy analysis in a wide variety of policy areas in which they are needed most. There has been no shortage of past attempts to think globally about the human condition or the long-range future. What has been missing, however, is a means of tying those efforts systematically and analytically to today's policy decisions. This is the gap the Pardee Center seeks to address.

Questions or comments about this Perspective should be sent to the lead author, Robert J. Lempert (Robert_Lempert@rand.org). Information about the Pardee Center itself and its other projects and initiatives is available online (www.rand.org/pardee). Further inquiries about Pardee Center activities and projects should be sent to the Pardee Center director, Robert J. Lempert, at Robert_Lempert@rand.org.

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