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Two Degrees of Innovation—How to seize the opportunities in low-carbon power: Executive Summary

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This paper offers a strategic framework for those seeking to capitalize on the low-carbon transition. The first section presents innovation as a key strategy to achieve economic development, energy, and environmental goals. The second section explains why the innovation process is unique in the low-carbon power sector and introduces the innovation ecosystem. The third section lays out a step-by-step process to identify and capitalize on the enormous potential and emerging opportunities in this sector.

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KEY POINTS

- A global transformation of the energy infrastructure is urgently needed to meet the need for modern energy services while avoiding a climate disaster.
- There is a large and growing global market for utility-scale, low-carbon power technologies as this transformation begins and both developed and emerging economies can benefit from it. But competing in the global value chain will require explicitly building innovation capacity.
- Innovation—improvements in price and performance—will close the gap between low-carbon technologies today and the low-cost, high-performance technologies that are needed.
- Innovations include new products, processes, or policies that reduce costs or improve performance and can happen at any point in a technology's lifecycle—from design through manufacturing through operations and maintenance.
- The innovation ecosystem approach captures the complexity, uncertainty, and heterogeneity of innovation processes and identifies the critical services innovators need to thrive. These are the services policymakers need to focus on when investing in innovation.
- The framework provides step-by-step guidance to identify the opportunities in the sector and build a robust innovation ecosystem to capture them.

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Why Innovate?

The world urgently needs a global transformation of the energy infrastructure—the very underpinning of the modern economic system. In order to avoid disastrous climate change, greenhouse gas emissions must be steeply cut in the coming years.[1] Simultaneously, 20 percent of the global population lacks access to modern energy services to fuel development.[2] Low-carbon technologies exist but are expensive compared to high-carbon alternatives and face performance challenges like requiring large quantities of water or land.[3] Innovation—improvements in price and performance—can deliver the cost-competitive, high-performance solutions needed to meet the dual energy challenges.

Low-carbon power is already a large and growing global market[4], and both developed and emerging economies have an opportunity to seize the economic growth associated with this transition. The framework in this paper is particularly addressed to decisionmakers in countries or regions who are struggling with how to capitalize on the opportunities in utility-scale, low-carbon power.

Innovation is central not just to meeting the intertwined energy access and climate change challenges. The capacity to continually innovate is critical to competing effectively in the global low-carbon value chain—the activities that develop, manufacture, install, operate, and integrate low-carbon power technologies. Innovation is crucial to reducing the environmental and human impacts of scaling up low-carbon technologies. Finally, innovation is essential to keeping electricity costs low while meeting these urgent challenges. There is little appetite in any country to raise energy prices, either by taxing high-carbon power (or reforming subsidies for fossil fuels) or subsidizing low-carbon power for a sustained period of time.

By investing in innovation, countries can reduce the cost of meeting climate and energy access challenges while increasing their international competitiveness in this growing sector.

The power sector is not the only part of the energy infrastructure that must be wholly transformed to meet the climate challenge. Accelerating innovation—and a framework related to the one described below—could be central to transformations in buildings, industry, and transportation. However, global supply chains and the highly regulated nature of utility-scale power present unique opportunities for innovation-led economic growth.

Can Innovation Deliver?

Can innovation really deliver a big enough change in the low-carbon power sector to meet the climate and energy access challenges policymakers face? As seen in the Solar Panel Cost and Area Changes figure below, successful innovations in materials, production processes, logistics, and other steps in the value chain underpin dramatic changes in cost and performance. The figure also highlights how low experts project innovation could drive costs in the future.

Innovation has not always happened at the breakneck pace seen in the twentieth century, and innovation in energy has often been painfully slow.[5] Nicholas Stern warns, the cost of actions to mitigate climate change "will be higher if innovation in low-carbon technologies is slower than expected".[6] It should not be assumed that innovation would happen fast enough to address the urgent challenges without support from policymakers.

Innovation Definitions

Innovation – a positive change in a process, product, or policy that reduces the cost or improves the performance of a solution. A *successful innovation* can be large or small and is adopted and used.

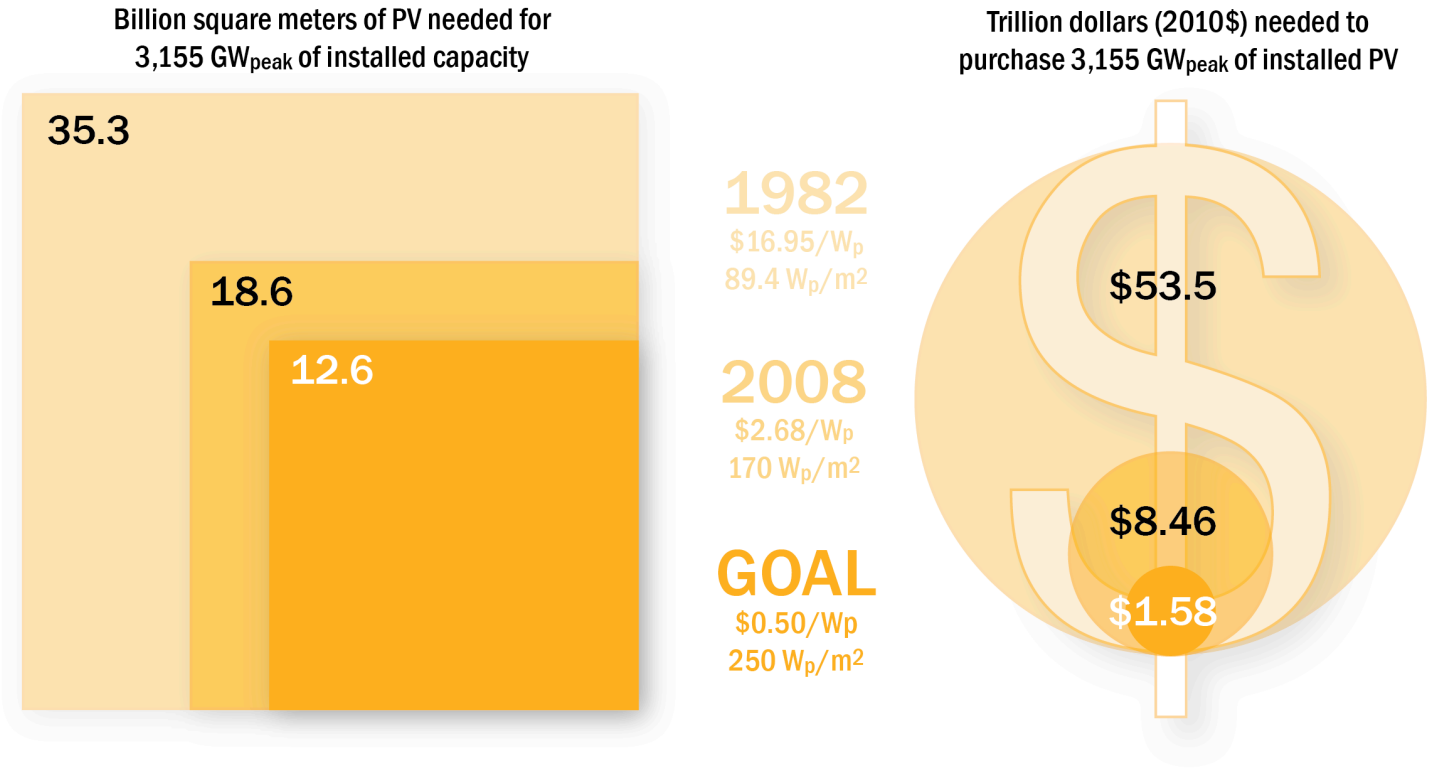
Innovation process – the iterative, interactive process that combines resources, including information, in new ways to better meet all of the market's requirements. Often this process is also called innovation.[7]

Innovation ecosystem – the actors who participate in or support the innovation process and the rules that shape their interactions. Also known as the innovation system.

Innovation ecosystem functions – the essential services that the participants provide each other in support of the innovation process. Effectively delivered functions improve the odds of success for an innovation process.

Solar Panel Cost and Area Change

The Role of Solar PV in reducing emissions 50% by 2050
using past, present, and future technology



To achieve a 50 percent reduction in greenhouse gas emissions by 2050 (compared to 2005 levels) the IEA estimates that 3,155 GW of photovoltaic capacity will be required by 2050, enough to provide 11 percent of global electricity production. Over time, innovations have made reaching this target easier. Innovations like new materials and improved methods of production, including improvements through learning-by-doing and finding economies of scale, have made solar photovoltaic cells significantly cheaper and more efficient between 1982 and 2008. While many factors—such as commodity prices—also impact costs, future innovations can continue to improve solar cells pushing toward a competitive cost of equipment, estimated to be US$.50/W.[8]

What is Innovation?

The reasons to invest in innovation are compelling, but the term *innovation* is badly overused and unclear. It is most common to think of innovations as things; new cell phones or medicines. However, innovations can also be new processes or organizations.[9] Successful innovations are adopted widely enough that they impact the marketplace. They can be large and revolutionary or small and incremental.[10] Given this breadth of opportunity, many people—from regulators to energy policymakers, from financiers to field technicians—are innovators every day.

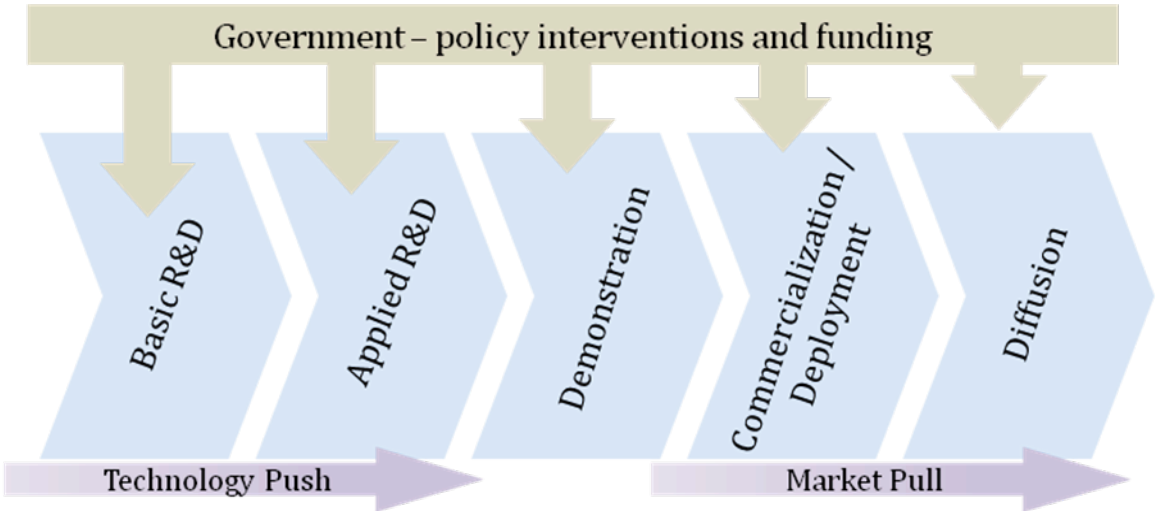
Innovation is often a synonym for innovation process; the way a new product or idea was developed and eventually diffused.[11] The innovation process is putting resources like capabilities, skills, knowledge, or new supplies together in a new way.[12] Often the innovation process in the power sector is represented as a linear process with predictable stages (see The Linear Innovation Process figure below).

Some power sector innovations do begin with basic science, and the linear model can be useful for considering issues like level of financing risk, but this model also has limits.[13] It does not effectively represent how complex, uncertain, and heterogeneous innovation processes can be.

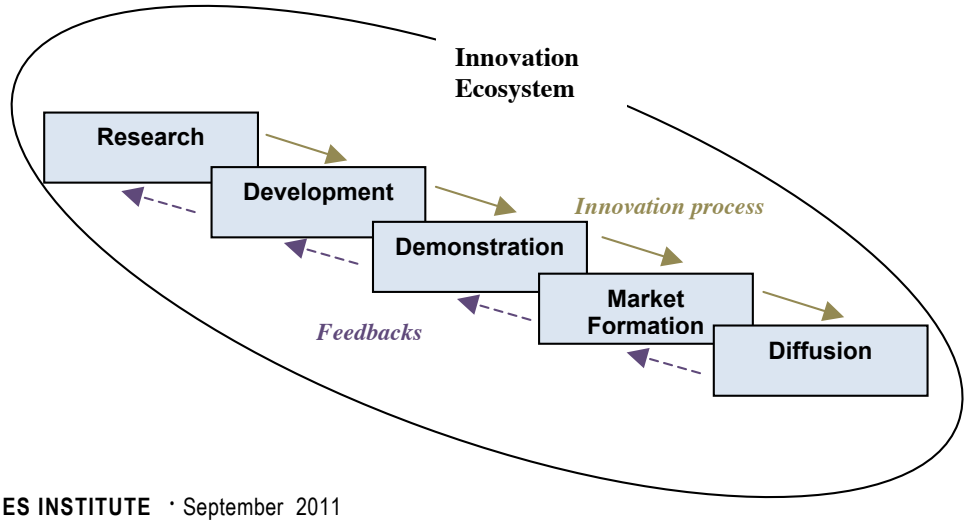
- Innovation processes are complex because the innovator might move back and forth between stages while trying to meet all the market criteria for a solution. There are many feedback loops between the stages.[14]
- Uncertainty hounds every step of an innovation process, from what the final solution will look like to how to reach it.[15]
- Every innovation process is unique. Some draw on science, others on technical know-how, new information about customers, or new suppliers. An innovation process can happen anywhere in the lifecycle of a product, from design, through manufacturing, to operations and maintenance (O&M).[16]

There have been attempts to articulate models that better capture these issues (see The Iterative Innovation Process figure below).[17] This model captures the many feedbacks and as a result some of the complexity and uncertainty seen in the real world. The more general phase names allow for more heterogeneity. The model also represents innovation processes supported by an innovation ecosystem, in which, as discussed below, policymakers are very active participants.

The Linear Innovation Process[18]



The Iterative Innovation Process[19]



Characteristics of Innovation in the Low-Carbon Power Sector

Low-carbon power technologies have some characteristics that strongly shape the innovation process and as a result, the sector.

- Because low-carbon technologies integrate with a very mature power sector, they are simply providing a commodity and as a result are price takers. They **cannot charge a premium** for the innovations they offer.[20]
- **Very large investments** are needed for many innovations and it can take a long time to reap the benefits of those investments.[21] This also makes updating designs and experimenting very slow.
- There are **diverse sources of new knowledge** in the sector: science, suppliers, customers, and others. Effectively accessing them is critical.
- **Knowledge is often tacit** (learned through experience rather than through blueprints or scientific articles). Even when it is not tacit, it is often effectively controlled.
- There are **many opportunities to innovate**, as the technologies are not yet mature.
- There are **few new entrants** and a relatively important role for **large, global players**. New entrants can rapidly move into the top tier with good strategies.
- There is a strong **geographic clustering** of innovators, often near customers.

Understanding how innovation shapes this sector is a powerful tool for the country or region looking for entry points in the value chain. Strategies that take these factors into account are more likely to be successful.

This more realistic model of innovation in the low-carbon power sector also suggests some key characteristics of the innovation process. Many of these point to how difficult and risky innovation is in this sector. So how do policymakers increase the odds of more innovation processes ending in success (i.e., widely adopted innovations)? By looking closely at the ecosystem that the innovation process happens within and actively supporting the functions of that ecosystem. The innovation ecosystem is composed of the actors who participate in innovation processes very broadly, and the rules that govern how they interact. All countries and regions have innovation ecosystems today, some functioning better than others.

This approach powerfully handles the realities of innovation. It assumes that change is ever-present and that the ecosystem is always evolving.[22] It focuses on learning and adapting to those changing circumstances, and making the best decisions possible with limited information.[23] It incorporates both the familiar market failures like underinvestment in research and non-market failures like how hard it is to absorb tacit knowledge.[24] Finally, it focuses on what support innovators in this sector need, and on domestic context, rather than on prescribing the 'right' way to deliver that support.[25]

The innovation ecosystem supports and unleashes innovators by providing them with services. To accelerate innovation, to increase the odds of innovation processes ending in success, it is critical to ensure all of the services or functions are being delivered. In the context of the low-carbon power sector, the critical functions that must be healthy and robust are listed below. These form the 'to do' list for the policymaker investing in innovation.

Innovation Ecosystem Functions in the Low-Carbon Power Sector

Function	Definition
Creating and sharing new knowledge	Some of the innovations in this sector are based on scientific discovery, but many find their source of inspiration in other areas. As a result, this function is broadly bringing new knowledge to the sector from all sources. Ensuring that knowledge spreads effectively through the sector is also critical.
Building competence	Skills in this sector are not easily learned from books and academic articles, but they are critical to the innovation process. Similarly, a basic education is critical but insufficient by itself. As a result, competence building—the provisioning of skilled human resources—is fundamental to successful innovation processes.
Creating collaborative networks	Networks are a fundamental tool for knowledge dissemination and creating the contacts innovators need to be successful. These can be market-based networks, such as with suppliers, but innovators also find mentors and other non-market support in their networks crucial. Networks can be local, regional, national, or international in nature.

Developing infrastructure	Innovation in this sector requires significant public infrastructure. Because the individual technologies are part of a larger electricity system and are often large pieces of infrastructure themselves, successful innovation activities rely on a significant physical infrastructure such as transmission.
Providing finance	Innovators often need access to capital in order to realize their solutions, whether they are a new manufacturing process or a different wind farm configuration. A range of financial actors with differing appetites for risk —public or private, domestic or international—must participate in order to serve needs throughout the innovation process.
Establishing governance and the regulatory environment	An innovation process is more likely to succeed when the rules of the game are clear and consistent. These rules tell the innovator the bounds within which he must work and the characteristics his solution must include. Unclear standards add to the uncertainty that already complicates any innovation process.
Creating markets	Policymakers have a strong hand in creating the power market and have a wide range of tools, from public awareness to mandates to government procurement, which can help ensure the ecosystem is creating a market that enables adoption of innovations.

Building a Dynamic Innovation Ecosystem

As national and regional policymakers build a dynamic innovation system, there is a range of policy tools available to promote innovation. For example, policies that invest in research and development (R&D) can induce innovation in low-carbon power generation, as can price mechanisms such as feed-in tariffs. How should a policymaker make sense of the pros and cons of competing proposals and choose between them? What analytical tools and methodologies are useful to help policymakers build an ecosystem that increases the odds of success for innovators? This section presents a framework to help policymakers build or strengthen a dynamic innovation ecosystem in the low-carbon power sector.

Steps to Build a Dynamic Innovation Ecosystem

Step 1: Global value chain assessment and positioning

Purpose: Decide which technologies and segments of the low-carbon power value chain will be the targets of innovation.

How: Conduct a landscape assessment of the country's or region's assets and capabilities and map these against opportunities in the global low-carbon power sector. Use this data to choose focus technologies and value chain segments.

Step 2: Ecosystem analysis

Purpose: Determine how well the current innovation ecosystem is delivering each critical function.

How: Conduct an analysis of innovation ecosystem functions for the technologies and segments of the low-carbon power sector selected in step one.

Step 3: Policymaking, design and implementation

Purpose: Reinforce functional strengths and correct systemic failures in the innovation ecosystem.

How: Select policy tools appropriate to the local context that will support the ecosystem functions.

Step 4: Policy evaluation, learning, and adaptation

Purpose: Monitor the impacts and the effectiveness of the adopted policies and changes in the sector. Make evidence-based adjustments to adapt to a rapidly maturing global sector.

How:

- Evaluate the impact of the policies implemented in step three on the innovation ecosystem functions.
- Evaluate whether innovation is accelerating through improved cost and performance metrics and whether this is achieving the economic development, energy, and environmental goals.
- Survey changes in the global sector.
- Update policy packages to adapt to the new situation.

STEP 1: Global Value Chain Assessment and Positioning

The first step is to assess a region or country's context and capabilities and match that against the opportunities in the regional or global low-carbon power sector. This landscape assessment helps determine where the country can most competitively participate in this growing sector. There are many ways to approach the analysis but below is one way to organize the inquiry.

The landscape assessment collects the critical information, but the important conclusion to this step is selecting the target low-carbon power technologies and segments of the value chain. In some cases, these choices have already been made, such as India's 2009 decision to invest heavily in solar. In this case, the landscape assessment can inform how to best achieve the announced goals and future updates of the goals. Goals in the low-carbon power sector, in turn, contribute to achieving broader economic development, energy, and environment goals, by narrowing in on the best opportunities for innovation-led economic development.

Landscape Assessment—Areas for Data Collection

	What to assess	Why is this relevant?
Context of the country or region		
Underlying characteristics	Relevant geographic features and natural resource endowments	Renewable and fossil fuel resources will significantly influence the way low-carbon technologies are evaluated. Geographic characteristics may set other important constraints such as availability of water or land needed to deploy specific technologies.
	Social aspects, including social characteristics and human capital variables	Social characteristics like prevailing language will influence the way that economic actors interact domestically and internationally. Flexible human capital variables, such as education level, will shape the capacity to innovate. Other human capital variables, such as population size and composition, will influence which niches and technologies will be most suitable to pursue.
	Political system characteristics and current political landscape	The political environment will shape which policy tools are available to pursue innovation in the low-carbon power sector. Existing political commitments and competing priorities might also pose restrictions or opportunities.
Current Economic Activity	Production structures and output of goods and services	Production structures will determine the strength and ability of the domestic economy to produce goods and services competitively.
	Trade patterns arising from the goods and services competitively produced	Existing patterns of international trade can reveal important insights about the capabilities embodied in the local economy, and about the existing links between local economic agents and those located in other countries and regions. This information will be valuable when assessing competitive strengths.
	Capabilities arising from the current production and trade portfolio	Existing capabilities may be useful in the low-carbon power sector. It is valuable to assess how the sector can make use of knowledge and human capacity from other developed industries.
	Macroeconomic and financial trends	Both the domestic and international economic environments will strongly influence a sector that is global by nature, and will shape the inputs and processes available to innovators.

	What to assess	Why is this relevant?
Energy Supply	Current energy provision setup	The way energy is produced, transmitted, and distributed in a country or region has a significant impact on how new low-carbon power generation technologies will emerge and operate.
	Current and future dependence on foreign sources of energy or other bottlenecks	These potential weaknesses in the energy supply will strongly impact social and political attitudes toward new policies and technologies to enhance domestic energy security. Dependence on other countries for oil, coal, or natural gas supplies may incentivize pursuit of domestic energy sources.
Environmental Considerations	Current and expected pressures on natural systems from human activity	Impacts from high-carbon power, like poor air quality, may help support a switch to low-carbon technologies. However, new low-carbon power technologies may create their own pressures on natural resources and ecosystems. Climate change may also impact natural resource endowments.
	Existing or potential commitments toward environmental sustainability	Commitments made by public authorities to pursue specific environmental outcomes, or the lack thereof, will impact the political will and investment needed to adopt new low-carbon technologies.
International Cooperation	Participation in international technology cooperation efforts	Involvement in internationally binding commitments, bilateral partnerships, and international organizations can either restrict or aid international cooperation. Domestic policies may also urge or restrict international cooperation.
	Availability of international climate finance	With commitments made by developed countries in the context of the UNFCCC negotiations to provide significant financial resources and the ongoing reprogramming of overseas development aid toward climate goals, developing countries may have opportunities to access funds to support their innovation ecosystems.
Factors related to each technology under consideration		
	Technology characteristics	Each technology will have characteristics that make it more or less attractive. A country or region may be better equipped to take part in one technological pathway over another, since innovation is always embedded in existing economic and social contexts.
	Value chain characteristics	The characteristics of the global value chain for each technology (customer base, manufacturing, transportation of goods, etc.) will be important in deciding which technological pathway to pursue and the best way to do so.
	International competition and interactions	There are high barriers to entry and very strong international price competition in most energy technologies. Innovation policy is not made in isolation, but partly in response to policies elsewhere. There may be niches, regional markets, or location-constrained parts of the value chain that do not face the same competitive pressure.
	Existing relationships with international investors, innovators, and supply chain partners	Interaction in an innovation ecosystem also occurs via transactions with investors, suppliers, customers, and via networking. These relationships will help determine the best technology or supply chain segment to pursue. Networks can take years to develop, so existing networks should be highly valued.

STEP 2: Ecosystem Analysis

The next step is to determine how effectively the innovation ecosystem functions are being delivered for the target technologies selected in step one. In this step is it critical to consult with stakeholders, particularly the innovators trying to succeed today.[26] This analysis should provide a good understanding of which functions are working effectively, which are facing systemic failures, and which could be bolstered to amplify their impact on the innovation process. The analysis in step one can provide much useful data, but now that a target technology has been chosen it is possible to delve deeper. The Analyzing Functions in the Innovation Ecosystem table provides example questions to effectively explore each function.

STEP 3: Policy Making – Design and Implementation

Step two identified systemic failures in innovation ecosystem functions that are impeding innovation. Building on this analysis, the next step is to design policy interventions to ensure functions are delivered more effectively. Rather than focusing on the individual policy tools (as it is impossible to make an exhaustive catalogue of options available), the framework provides principles to ensure a maximum impact on the innovation ecosystem.

- *Focus on improving the rate of change in price and performance.* Rather than trusting that increased deployment of technologies implicitly leads to innovation, policies should explicitly drive lower costs and improved performance through features like declining subsidies or tightening pollution controls.
- *Design polices that are context-dependant and locally appropriate*. The innovation ecosystem approach explicitly acknowledges that there can be tremendous differences between policy contexts. Best practices can be adapted but policies and strategies cannot be adopted wholesale from another context.
- *Take a functional approach rather than a tool-centric approach*. Many different policy tools can effectively improve how well a function works. The goal is not to deploy a tool, like a renewable portfolio standard, because it is a standard policy prescription, but because it will improve the function.

Analyzing Functions in the Innovation Ecosystem

Function	Sample Evaluation Questions
Creating and sharing new knowledge	Are local institutions generating new knowledge or does most knowledge come through foreign players? Are government and private sector R&D budgets stagnate or even declining? How is new knowledge shared, particularly if it is non-competitive or public data?
Building competence	How flexible is the skilled workforce to adapt to this changing sector? Do they have access to the specialized training, either domestically or abroad, needed for these technologies?
Creating collaborative networks	Are there collaborative networks for the flow of information, products, and services between private sector companies, research institutes, academic institutions, and other stakeholders?
Developing infrastructure	Are the key infrastructure elements, from roads to heavy equipment, from a functioning grid to manufacturing facilities, in place to support innovators?
Providing finance	Can innovators access finance throughout the innovation process? Is a range of actors participating, each with a different appetite for risk? Do the traditional sources of finance, such as banks, understand the new sector and choose to participate in it?
Establishing governance and the regulatory environment	Do the rules of the game provide space for new ideas and approaches? Do they create incentives for innovation in this sector or discourage action? Are they clear and stable, and do they limit the transaction costs of compliance? Do they appropriately set the environmental and other public requirements for new technologies?
Creating markets	Does a market for these technologies currently exist domestically? If building an export potential is one of the larger goals, how are the markets in the target countries? Are there explicit barriers to participating in those markets?

- *Design integrated and interconnected policies*. Collaboration with other policymakers will be critical to improving every function at the regional, national, and international level. However, large, sweeping packages may be difficult to implement so smaller, interconnected improvements can also be pursued.
- *Design durable, incremental policies to achieve cumulative change*. Politics and other factors like absorptive capacity may limit the scale of the policy changes that are possible. Incremental changes, which can be more durable despite changing political winds, can be very important to the ecosystem's future path, though it is important that these incremental changes are well telegraphed to innovators so they do not increase uncertainty.
- *Design robust but flexible policies*. The one certainty in this sector is constant change. Whether from the impacts of climate change or the policies of another player in the sector, policies that will work in multiple future scenarios are more likely to contribute positively to the ecosystem rather than create systemic failures of their own.
- *Design with evaluation and learning in mind*. In this iterative process, it is critical to evaluate policies to learn and adapt. Strategies from small-scale experiments to reporting requirements can make this process more successful.

STEP 4: Policy Monitoring, Evaluation, Learning, and Adaptation

At this point a target technology has been chosen based on a country's strengths, resources, and capabilities; the effectiveness of the ecosystem functions has been evaluated; and policy instruments meant to improve the effectiveness and efficiency of the functions have been designed and implemented. Building a dynamic innovation ecosystem is an iterative process so the next step is to evaluate the policies set in step three, scan for changes throughout the global sector, and make any changes necessary to adapt to the new challenges and opportunities. Without continued monitoring and adaptation, new systemic failures can emerge and old ones fester.

Sample Policy Tools by Ecosystem Function

Function	Tools
Creating and sharing new knowledge	Subsidies and incentives for new research contests and prizes, intellectual property protection and enforcement measures
Building competence	Subsidies and incentives for education and training, fellowships, scholarships, visas for advanced degree candidates
Creating collaborative networks	Joining or initiating international cooperation, supporting industry associations, intellectual property protection and enforcement measures that provide network participants confidence
Developing infrastructure	Public-private partnerships, incentivizing private development, planning for public development, investment in public infrastructure
Providing finance	Loan guarantees, 'green' banks, public venture capital style funds
Establishing governance and the regulatory environment	Setting standards, setting targets, taxing negative externalities, subsidizing positive externalities, eco-labeling and other voluntary approaches, tradable permits
Creating markets	Feed-in tariffs, renewable portfolio standards, government/public procurement, media campaigns, setting government requirements, taxing negative externalities, subsidizing positive externalities, eco-labeling and other voluntary approaches

Evaluation should encompass three levels of analysis:

- Were the policies successfully implemented and how did they impact the delivery of ecosystem functions?
- Is the innovation ecosystem successfully accelerating innovation? Are costs declining and performance improvements emerging?
- How is the country or region progressing toward its long-term development goals? For example, is an export industry developing and drawing foreign direct investment?

Given the rapid change in this sector, monitoring the state of both the national context as identified in step one and the innovation ecosystem as identified in step two is critical. While the policies may have been implemented perfectly, the larger landscape will likely have changed, either blunting or amplifying the policies' impact. New opportunities may have emerged and new competitors evolved.

Finally, it is critical to adapt—to change, tune, cancel, or update the policies put in place in step three—to cope with the new landscape and to incorporate the learning from the evaluation process.

Conclusion

The need for innovation in the low-carbon power sector is critical, both in terms of our challenges—preventing catastrophic climate change and addressing urgent development gaps—and in terms of opportunities to participate in the economic growth that will go with it. Policymakers need better evidence as they chart a course through this new territory and they need to be able to share their experiences and learn together.

In the end, it is likely the global power sector will be transformed through a blend of strategies; increasing the cost of high-carbon options or limiting them outright and reducing the cost of the low-carbon alternatives. The power sector is not the only one that requires transformative change and there are important synergies between it and demand-side changes, distributed supply options, and transportation solutions that this analysis misses. In each of these, innovation is key to effectively using the best technology to meet our challenges.

There have been a great many technological revolutions in the last two hundred years, from agriculture to energy to information. Solving the pressing problems of today requires everyone to live up to their potential as innovators and contribute to the next revolution.

REFERENCES

[1] Intergovernmental Panel on Climate Change, Working Groups I, II and III, *Climate Change 2007: Synthesis Report*, IPCC Assessment Report (Valencia, Spain, 2007), http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf; Nicholas Stern, "Summary of Conclusions," in The Economics of Climate Change (New York: Cambridge University Press, 2007), xv-xvii.

[2] International Energy Agency, "Access to Electricity," *World Energy Outlook*, 2010, http://www.worldenergyoutlook.org/electricity.asp.

[3] Ottmar Edenhofer et al., *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation - Summary for Policymakers* (Cambridge, United Kingdom and New York: Intergovernmental Panel on Climate Change, 2011), http://srren.ipcc-wg3.de/report/IPCC_SRREN_SPM.

[4] REN21, *Renewables 2011 Global Status Report* (Paris: REN21 Secretariat, July 12, 2011), http://www.ren21.net/Portals/97/documents/GSR/REN21_GSR2011.pdf.

[5] Jan Fagerberg, "Innovation: A Guide to the Literature," in *The Oxford Handbook of Innovation* (Oxford: Oxford University Press, 2006); Peter Fox-Penner, *Smart Power: Climate Change, The Smart Grid, and the Future of Electric Utilities* (Washington, D.C.: Island Press, 2010).

[6] Nicholas Stern, "Summary of Conclusions."

[7] Carol Slappendel, "Perspectives on Innovation in Organization," *Organization Studies* 17, no. 1 (January 1996): 107.

[8] These calculations focus on crystalline silicon photovoltaic technology only, assume photovoltaic cells operate at peak capacity, and only consider module cost. For simplicity, many other factors that can make solar photovoltaic installations more efficient and cheaper are excluded, including careful siting, improved operations, and reduced maintenance costs. This includes only the solar module cost and omits installation and maintenance costs.

Sources:

IEA Solar PV Energy Roadmap Goal - Paolo Frankl et al., *Technology Roadmap: Solar photovoltaic energy, Technology Roadmaps* (Paris, France: International Energy Agency, 2010), http://www.iea.org/papers/2010/pv_roadmap.pdf.

1982 Values - P. McGuire and P. Henry, *Electricity from Photovoltaic Solar Cells: Flat-Plate Solar Array Project: Volume VIII Project Analysis and Integration* (Jet Propulsion Laboratory for the US Department of Energy, October 1986).

2008 Values - Frankl et al., *Technology Roadmap: Solar photovoltaic energy, Technology Roadmaps*.

Goal of $1/Watt - *$1/W Photovoltaic Systems: White Paper to Explore A Grand Challenge for Electricity from Solar*, $1/Watt Workshop (Advanced Research Projects Agency-Energy, US Department of Energy, 2010), http://www1.eere.energy.gov/solar/sunshot/about.html.

Inflation between 1982 and 2008 was accounted for using the U.S. BLS CPI Inflation Calculator available at: http://www.bls.gov/data/inflation_calculator.htm. Accessed August 2011.

[9] Slappendel, "Perspectives on Innovation in Organization."; Fagerberg, "Innovation: A Guide to the Literature", 1-26; Jon-Arild Johannessen, "A systemic approach to innovation: the interactive innovation model," *Kybernetes* 38, no. 1/2 (2009): 158 - 176.

[10] Fagerberg, "Innovation: A Guide to the Literature."

[11] Slappendel, "Perspectives on Innovation in Organization."

[12] Joseph Schumpeter, *The Theory of Economic Development* (Cambridge, MA: Harvard University Press, 1934); Jon-Arild Johannessen, Bjorn Olsen, and G.T. Lumpkin, "Innovation as newness: what is new, how new and new to whom?," *European Journal of Innovation* 4, no. 1 (2001): 20, http://www.emeraldinsight.com/journals.htm?issn=1460-1060&volume=4&issue=1&articleid=872497&show=pdf; Slappendel, "Perspectives on Innovation in Organization."

[13] Stephen Kline and Nathan Rosenberg, "An Overview of Innovation," in *The Positive Sum Strategy: Harnessing Technology for Economic Growth* (Washington, D.C.: National Academy Press, 1986), 275 - 305, http://books.google.com/books?id=8zErAAAAYAAJ&printsec=frontcover&dq=Positive+sum+strategy&hl=en&ei=KceTYarGYro0QGN5ozGBw&sa=X&oi=book_result&ct=result&resnum=1&ved=0CDYQ6AEwAA#v=onepage&q&f=false; David Mowery and Nathan Rosenberg, "The influence of market demand upon innovation: a critical review of some recent empirical studies," *Research Policy* 8, no. 2 (1979): 102-153.

[14] Andrew Van de Ven et al., *The Innovation Journey* (Oxford: Oxford University Press, 2008); Kline and Rosenberg, "An Overview of Innovation."

[15] Schumpeter, *The Theory of Economic Development*, 85; Richard Nelson and Sidney Winter, *An Evolutionary Theory of Economic Change* (Cambridge, MA: Harvard University Press, 1982), 129; Kline and Rosenberg, "An Overview of Innovation," 294; Fagerberg, "Innovation: A Guide to the Literature," 5; Van de Ven et al., *The Innovation Journey*.

[16] Keith Pavitt, "Innovation Processes," in *The Oxford Handbook of Innovation* (Oxford: Oxford University Press, 2006), 87.

[17] Kline and Rosenberg, "An Overview of Innovation," 289; Van de Ven et al., *The Innovation Journey*, 25.

[18] Michael Grubb, "Technology Innovation and Climate Change Policy: an overview of issues and options," *Keio Economic Studies* 41, no. 2 (2004): 103-132, http://www.econ.cam.ac.uk/rstaff/grubb/publications/J38.pdf.

[19] This figure is adapted from *The Great Green Technological Transformation*, World Economic and Social Survey (New York: United Nations Department of Economic and Social Affairs, 2011), 136, http://www.un.org/en/development/desa/policy/wess/wess_current/2011wess.pdf., which itself draws from forthcoming background papers by A. Grubler and K. Sims Gallagher.

[20] Charles Weiss and William Bonvillian, *Structuring an Energy Technology Revolution* (MIT Press, 2009).

[21] Kelly Sims Gallagher, John P. Holdren, and Ambuj D. Sagar, "Energy Technology Innovation," *Annual Review of Environment and Resources* 31, no. 1 (November 2006): 193-237, http://www.annualreviews.org/doi/full/10.1146/annurev.energy.30.050504.144321.

[22] Charles Edquist, "Systems of Innovation: Perspectives and Challenges," in *The Oxford Handbook of Innovation* (Oxford: Oxford University Press, 2006), 182 - 208.

[23] Jorge Niosi, *Building National and Regional Innovation Systems: Institutions for Economic Development* (Edward Elgar Publishing, 2010), 34.

[24] *Dynamising National Innovation Systems* (OECD Publishing, 2002), http://www.oecd-ilibrary.org/industry-and-services/dynamising-national-innovation-systems_9789264194465-en.

[25] Niosi, *Building National and Regional Innovation Systems: Institutions for Economic Development*; Richard Nelson, ed., *National Innovation Systems: A Comparative Analysis* (New York: Oxford University Press, 1993).

[26] Bengt-Åke Lundvall and Susana Borrás, "Science, Technology, and Innovation Policy," in *The Oxford Handbook of Innovation* (Oxford: Oxford University Press, 2006), 614.

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