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

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This paper offers a strategic framework for policymakers 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 approach. The third section lays out a step-by-step process to identify and capitalize on the enormous potential and emerging opportunities in this sector. The first two sections provide important foundations to the framework, but can be read separately.

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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. 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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EXECUTIVE SUMMARY

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

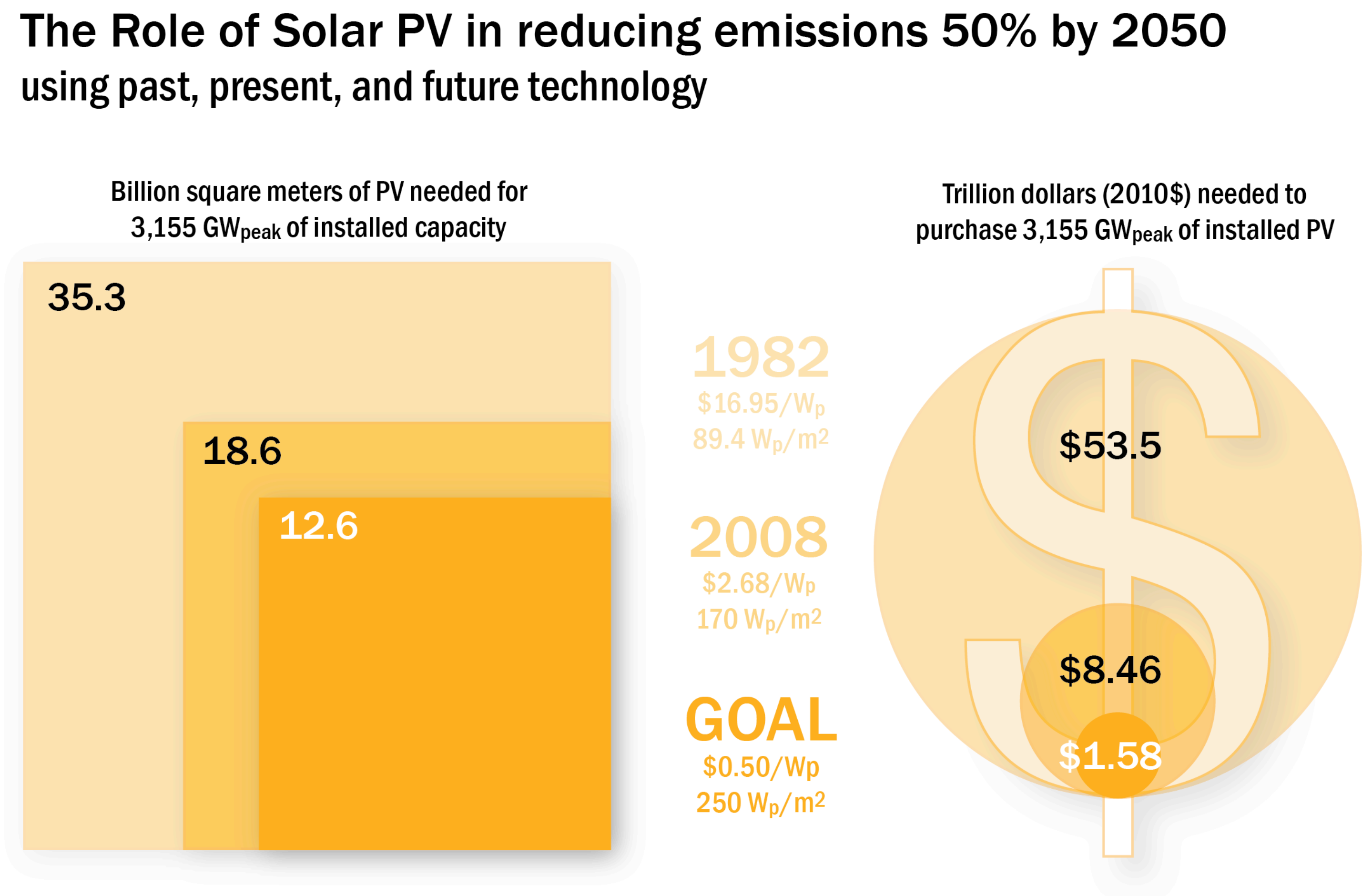
Innovation – a positive change in a process, product, or policy that reduces the cost or improves the performance of a solution. A *successful innovation* can be large or small and is adopted and used.

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



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.

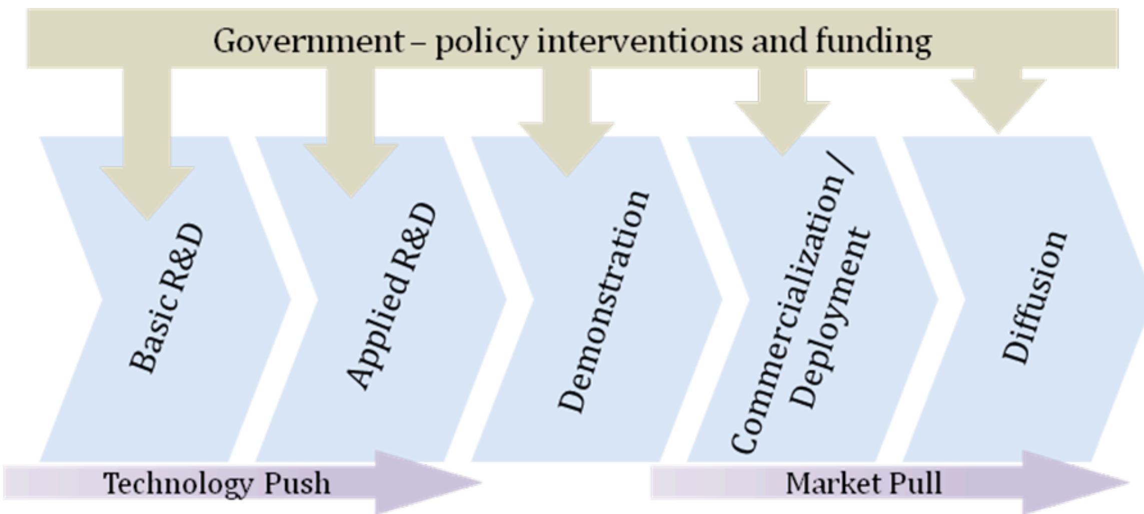
Innovation is often a synonym for innovation process; the way a new product or idea was developed and eventually diffused.[11] The innovation process is putting resources like capabilities, skills, knowledge, or new supplies together in a new way.[12] Often the innovation process in the power sector 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.

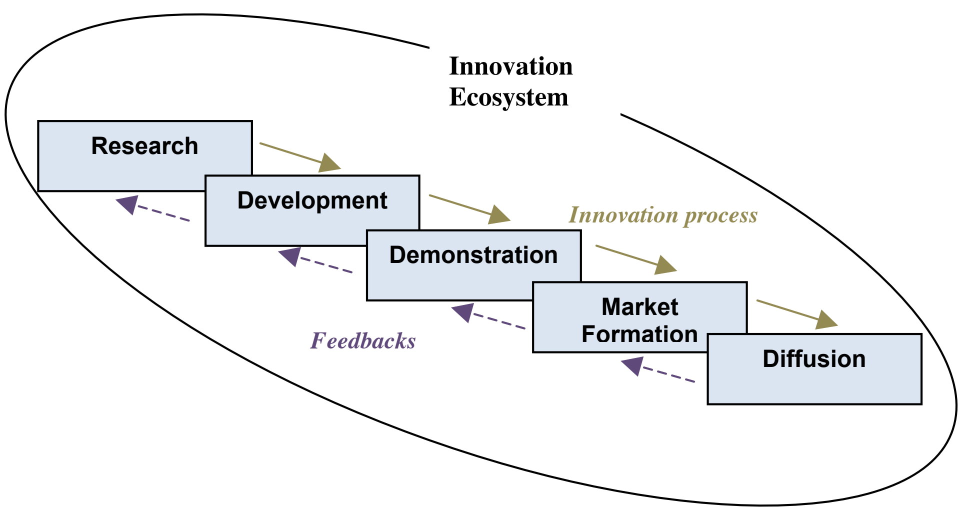
- Innovation processes are complex because the innovator might move back and forth between stages while trying to meet all the market criteria for a solution. There are many feedback loops between the stages.[14]
- Uncertainty hounds every step of an innovation process, from what the final solution will 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.

INTRODUCTION

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. [27] Simultaneously, 20 percent of the global population still lacks access to the modern energy services needed to fuel development.[28] Many more lack access to reliable, affordable modern energy. These intertwined needs challenge policymakers in both developed and developing countries.

The necessary technologies exist today to move away from greenhouse gas emitting energy technologies, particularly in the power sector. For example, a recent Intergovernmental Panel on Climate Change (IPCC) report confirmed that the global technical potential for renewable energy is substantially larger than global energy demand.[29] However, many low-carbon energy technologies are more expensive than their carbon emitting counterparts. They face performance challenges, like requiring significant water or land. They are new to the energy system and create integration headaches. While the climate challenge can be met with the tools on hand, **innovation—improvements in cost and performance—can deliver the cost competitive, high performance solutions needed to meet the dual energy challenges.**

The energy transition has begun. Current national commitments to low-carbon power are creating **a sizable global market for utility-scale, low-carbon power technologies**. Governments are moving from pledges to action, implementing their international and domestic commitments under the umbrella of low emissions development strategies and green growth.

- In 2010 investment in renewable energy generating capacity (including large hydro) was greater than fossil-fuel investment.[30]
- "Total investment in renewable energy reached $211 billion in 2010, up from $160 billion in 2009. Including the unreported $15 billion (estimated) invested in solar hot water collectors, total investment exceeded $226 billion. An additional $40–45 billion was invested in large hydropower."[31]
- "For the first time, investment in renewable energy companies and utility scale generation and biofuel projects in developing countries surpassed that in developed economies."[32]
- "Renewable energy accounted for approximately half of the estimated 194 gigawatts (GW) of new electric capacity added globally during the year."[33]

This sector is rapidly growing and the potential for further expansion is substantial. The IEA estimates that the total investment needed to achieve a 90 percent reduction in the carbon intensity of electricity generation by 2050 (compared to 2007 levels) is US$32.8 trillion.[34] **Countries, both developed and developing, have an opportunity to seize the economic growth associated with this transition.**

Past waves of innovation, such as the information technology revolution, have been exported from developed to developing countries. This time emerging economies already have some capacity to lead innovation in critical parts of the low-carbon power sector and are making truly massive investments in both research and development[35] and energy infrastructure.[36] China is the example most often touted, but others could also play important roles. Emerging economies are making these investments because they provide a crucial competitive edge in this rapidly moving sector.[37] **Securing a place in the global value chain—the activities that develop, manufacture, install, operate, and integrate low-carbon power technologies—will require explicitly investing in innovation.**

In most models of a low-carbon future, such as those done by the International Energy Agency (IEA), **innovation is assumed to occur and to reduce costs over time.[38] There has been less focus on *how* to ensure this innovation takes place**. What is the appropriate role of the policymaker? Will increased deployment alone drive down cost and improve performance or does the need to be globally competitive mandate more active support for innovation? Meanwhile, decades of research have examined how innovations emerge in other sectors, what factors improve the odds of success in innovation processes, and how innovative capacity is intertwined with economic growth. This literature has not previously been applied to the low-carbon power sector, but it does support a framework for action. Gleaning principles for the newly emerging sector from the existing evidence base for innovation-led economic development provides a wealth of tools for policymakers.

This paper provides a framework for policymakers to foster innovation in order to seize the opportunities presented by the global utility-scale power sector transformation, helping to answer the critical question, "How do I in practice bring home the benefits of low-carbon development and green growth?"

Audience

This paper provides national or regional policymakers with analytical tools and methodologies to seize this opportunity, maximize the benefits from their investments, and deliver both near- and long-term benefits to their constituents. The scope of analysis is limited to the low-carbon electricity generation sector (also called the low-carbon power sector), because this delineates a common set of global participants, regulatory structures, and challenges. The supply side of the power sector is not the only priority area of energy in need of transformation though; this framework could be similarly applied to the demand side of electricity, to transport and to industrial efficiency. The principles described here are also broadly applicable to the innovation needed to support adaptation to a changing climate. Many discussions about innovation principles in climate change mitigation try to address this much broader range of sectors. This paper is more narrowly focused in order to provide tools that give enough specificity to act.

This focus on a single sector still incorporates a large and diverse audience. Policymakers in both developed and emerging economies are facing similar technical questions and political challenges as they grapple with delivering a low-carbon power transformation with limited public budgets and price sensitive consumers. While there are differences in the resources they have to work with, they are driven by similar concerns about cost containment, economic development, energy security, and environmental sustainability. Work on this topic often falls to an energy ministry, but integration with economic development ministries is critical to capturing the larger benefits of the growing low-carbon power sector. Because this approach is so tightly tied to economic development, these tools are also broadly useful to those providing technical support or financial support for economic development internationally, such as the multilateral development banks and overseas development agencies.

Methodology

We began with a comprehensive literature review to underpin our efforts to identify why innovation is key to solving the challenges facing the power sector and how policymakers might support innovators. We drew primarily from scholarly peer-reviewed sources, governmental and trade publications, and institutions, such as the OECD, with a long history of research in this area. Identifying and drawing upon seminal articles—selected through cross-referencing bibliographies and citation searches—yielded foundational works stretching back to the 1930s, beginning with Joseph Schumpeter writing on innovation in economic development. More recent works covering innovation and its processes, systems, and applications included Chris Freeman, Richard Nelson, Bengt-Åke Lundvall, Keith Pavitt, and others. Contemporary research by others, such as Jorge Niosi and Andrew Van de Ven, supplemented the seminal articles to support the evaluation, analysis, and interpretation of concepts to be applied to the low-carbon power sector. Illustrations were drawn from trade press and governmental sources, as well as academic sources writing on energy policy. This body of literature encompassed analysis of:

- innovation in emerging and mature sectors,
- innovation strategies and economic development in developed, recently developed and emerging economies,
- product, process, and organizational innovations,
- local, national, and global innovation processes, and
- successes and failures in innovation policy efforts.

Taken together, this literature drew a comprehensive picture of the current understanding of how innovation is a central driver of economic growth and how it is most effectively fostered. This understanding of how innovation is best fostered is particularly powerful in light of the focus on green growth in policy circles and the need for innovation in low-carbon technologies.

Structure

The paper opens by reviewing why innovation is critical to meeting policymaker's development, energy, and environmental goals. Section two introduces foundational concepts about innovation processes and the ecosystem that supports innovators. It concludes by detailing what innovation concepts can reveal about how the low-carbon power sector operates today. Section three introduces a step-by-step process for policymakers who want to invest in innovation in order to seize the opportunities. It describes how to identify opportunities in the sector, how to assess the current innovation ecosystem and how to take steps to bolster support for innovations.

SECTION 1—WHY INNOVATE?

Policymakers should embrace innovation in the low-carbon power sector for a host of reasons integral to economic development, energy, and environmental agendas in both developed and developing countries. From efforts to drive economic growth to supplying low-cost electricity, from creating new jobs to safeguarding the climate, the potential benefits derived from investing in low-carbon power sector innovation should not be ignored.

Innovation for Economic Growth and Development

Innovation is one of the most important drivers of economic growth. Schumpeter was the first economist to highlight that knowledge and innovation are critical to the evolution of an economy. He remarked that a “new combination of the means of production” is “the fundamental phenomenon of economic development”.[39] Solow was the first modern economist to bring technology into neoclassical economics and show that it has an important role to play in long-term growth.[40] Since Solow’s contribution over 50 years ago, the role of technology and innovation have been extensively explored by modern economists,[41] and most agree that improvements in these areas are the main engine to increases in long-term productivity and economic growth.[42] Improvements in technology and productivity are one of the three factors that explain growth, alongside increases in capital and labor. **In many countries, total factor productivity (a broad definition of technology usually employed by growth economists) was found to account for more than half of long-term economic growth.[43]** There is little disagreement that innovation is itself a critical ingredient to the economic development of any country.[44] For example, the dramatic growth episodes in the so-called Southeast Asian Tigers have been extensively studied and linked to their successful efforts to create and foster new sectors through a mix of industrial, science, technology, and innovation policies.[45]

The argument that innovation leads to growth is also relevant to specific sectors. Fostering innovation in a specific sector is often a more manageable task than attempting to do so across the entire economy simultaneously. Even high-capacity nations tend to focus efforts on key sectors.[46]

The emerging low-carbon power sector has become a priority for many nations pursing development. Countries like China have explicitly targeted the low-carbon power sector as a new strategic sector leading economic growth worldwide.[47] By early 2011, at least 95 countries had enacted policy mechanism to support renewable electricity generation, more than half of which developing countries.[48] This sector has been experiencing impressive growth rates in recent years, with little indication that this rapid expansion is short-lived.[49] Investing in innovation in low-carbon power technologies is thus particularly attractive for two reasons: first, because the power sector usually forms an important share of a country’s overall economy, and impinges on nearly all other sectors through energy provision services; and second, because past experience suggests that rapidly-growing, technologically-advanced sectors have been good targets for policy interventions aiming to spur a country’s economic performance, or “leapfrogging” into sustained international competitiveness.[50]

Participating in the low-carbon power sector requires interaction with global markets, which creates opportunities for significant economic benefits in and of itself.[51] The larger, international market increases the opportunities for learning, for access to innovations made elsewhere, and for additional exports. Developing nations may not have sufficient resources for early-stage research and development, education investment, or competitive innovation strategies to penetrate the global market.[52] Participation in a global energy innovation ecosystem therefore allows for short-term capacity expansion through adoption of the most appropriate technologies available on the global market, which should be adapted to the country context. Over time, countries can develop technologies and processes in the low-carbon power sector ideal to their specific local contexts, incorporating existing indigenous knowledge from other economic sectors (cross-sector transfer or "skill switch"). This would allow them to capture critical links within the global supply chain and expand market share, which increases rates of wealth retention and contributes to domestic economic growth and welfare.[53]

Innovation in the low-carbon power sector also provides numerous development co-benefits beyond its direct contribution to economic growth, such as improvements in:

- access to education services,
- human capital due to training and absorption of know-how,
- public health outcomes due to the increased use of clean fuels,
- government regulatory practices and institutions available to other sectors,
- wage levels,
- trade balances along with shallower economic cycles (in the case of countries highly dependent on imports of fossil fuels and their price fluctuations in international markets), and
- access to energy resources.

In turn, these development co-benefits help to increase economic and political performance and stability, augmenting investor confidence and leading to increases in foreign direct investment. This brings additional resources to the country and may enhance knowledge and technology spillovers, creating a virtuous cycle that feeds back into innovation processes across the economy.[54]

Innovation for Expanded, Affordable, and Reliable Electricity Access

Expanded Electricity Access

Innovation in the low-carbon power sector is necessary to expand both physical and economic access to electricity and modern energy services. According to the International Energy Agency's 2010 World Energy Outlook, the world's average electrification rate as of 2009 was 78.9 percent, leaving 1.4 billion people or over 20 percent of the world's population without access to electricity, and consequently without access to the benefits of modern energy services such as lighting, refrigeration, and telecommunications.[55]

Innovation throughout the entire low-carbon value chain—including in renewable energy equipment manufacturing, electricity generation, transmission, dispatching, demand management, and policy and regulation—**is key to bringing electricity prices down while improving access and performance** (be it reliability, efficiency, safety, quality, or similar criteria). Solving the inter-related physical and economic challenges to providing modern energy services requires technologies that meet consumers' performance needs, avoid damaging the climate, and cost the same or less than fossil fuels or traditional energy sources. Innovation is key to fulfilling all of these criteria.

Transmission is an ideal example of why innovation is central to providing clean, cheap, and reliable power. Development of low-carbon power from renewable sources like wind and solar requires that the electricity sector balance both the temporal variability and the geographic mismatch of renewable energy generation and large-scale electricity demand.

Both technical and systems innovations—for example ultra high-voltage transmission lines, real-time dispatching, renewable resource forecasting, large-scale electricity storage, and demand side management—are needed for low-carbon producers to contribute their power to the grid and to ensure the provision of sustainable and reliable power.[56]

Energy Security

Policymakers strive to consistently deliver affordable electricity as a central ingredient for economic development.[57]

They also strive to keep prices relatively stable. High or volatile energy prices have led to civil unrest and to the downfall of elected government officials in developed[58] and developing countries.[59] The economic effects from such delivery and price disruptions can have broad impacts, affecting household-level consumers, a country's macroeconomic activity, and foreign exchange balances.

Innovation can improve both economic and physical energy security by reducing supply vulnerabilities and limiting price volatility in two crucial ways. First, innovation can help increase the efficiency of electricity generation, regardless of fuel type. More efficient plants require less fuel to meet the same demand, reducing exposure to supply disruptions and price volatility.

Second, innovation can increase the share of electricity produced from renewable sources relative to fossil fuels. By relying less on fossil fuel sources, whose prices are often driven by global market forces, and more on renewable energy sources, which have little or no fuel costs, the power sector can increase the stability of electricity prices. Moreover, if the renewable resources are available domestically, physical energy security can also be increased.

Innovation that increases reliance on renewable energy can also help countries hedge against medium- and long-term future fossil fuel price increases. Over time, the price of renewable energy technologies, such as solar panels, is expected to decline,[60] and the price of conventional fossil-fuel-generated electricity will likely continue to rise.[61] India, for example, is embracing solar energy as an imperative to protect itself from higher dependency on imported coal and the related cost of developing import infrastructure.[62] The Philippines is similarly using renewable energy investments to hedge against rising fossil fuel prices.[63]

Innovation for Climate and the Environment

Meeting the Climate Challenge

In the face of clear and robust scientific evidence of global warming and its anthropogenic causes, the primary policy response is a reduction in greenhouse gas (GHG) emissions.[64] The international community now broadly agrees on the need to limit climate change to 2°C of average global warming above pre-industrial levels.[65] While groups of nations and individual countries are taking action, such as the European Union's commitment to reduce its emissions to at least 20 percent below 1990 levels by 2020[66], summed together, countries' declared first steps still are not enough.[67]

Box 1 | Making Low-Carbon Power Economically Competitive

There are several ways to make low-carbon energy technologies cost competitive with high-carbon options in order to enable the power sector transition. The first strategy is to increase the cost of the high-carbon options. This can be done by removing or reforming subsidies for fossil fuel energy, as discussed by the G20 in 2010.[68] It can also be done by including diffuse costs, like health impacts and climate change, associated with high-carbon options in the cost of the power. A carbon tax or carbon-trading schemes, like the European Union Emissions Trading Scheme, are familiar. Regulation that tries to limit pollution to economically efficient levels under a cost/benefit analysis is also an option.

Raising the cost of high-carbon options would make it easier for low-carbon options to economically compete, particularly technologies like carbon capture and storage, which will never be able to compete with unregulated high-carbon technologies. But higher electricity prices are politically difficult, even if they are justifiable in terms of long-term environmental and social benefits. Countries worry that they will undermine the international competitiveness of export industries, will drive energy intensive industries to unregulated economies, and will dampen economic growth.

The second strategy is to drive down the cost of low-carbon options by investing in innovation. In the case of CCS, this limits the overall electricity price increase needed to address carbon pollution. With other technologies, like wind power, innovation could lead to undercutting high-carbon options altogether.

The two approaches are complimentary and reinforce each other in trying to reach cost competitiveness. In the current economic climate, strategies that reduce energy costs while reducing environmental impacts and creating development co-benefits, as innovation does, may be easier for policymakers to implement.

Peaking of atmospheric CO_2 concentrations in time to limit warming to 2°C will be virtually impossible without accelerated clean technology innovation.[69] Wind turbines need to capture more energy. Solar cells need to be more efficient. Geothermal technology needs to be further adopted. Carbon dioxide capture and storage (CCS) needs more efficient capture technologies that ensure safe and permanent storage. The costs of all these technologies need to fall. **Innovation is crucial to lower the cost and increase the adoption of low-carbon energy resources, thereby helping mitigate climate change**.

Environmental Preservation

However, low-carbon technologies are not themselves free of environmental impacts. **Innovation is necessary to reduce the power sector's impact on people and ecosystems**, including the negative environmental impacts associated with the scale-up of low-carbon power technologies. Three important performance criteria are efficiency, safety, and efficacy:

1. Efficiency improvements in low-carbon power generation reduce the amount of natural resource inputs that are needed to generate a unit of electricity output. Efficient resource use and management is key to reducing pressure on the environment. For example, innovation that improves the efficiency of photovoltaic panels reduces the amount of land surface that is necessary for utility-scale solar-powered electricity generation. Innovation in second-generation cellulosic ethanol reduces the amount of arable land, water, and fertilizer otherwise needed to grow crop biofuels.
2. Safety and quality improvements can facilitate the acceptance of renewable energy technologies, particularly in populated areas, and help ensure people and ecosystems are protected and risks are mitigated. For example, innovation that strengthens wind turbines to better withstand strong winds and extends their lifespan increases their safety and acceptability for onshore wind farms near human populations.
3. Efficacy is also critical to ensure that low-carbon power generation has the desired impact on the climate. Net GHG emissions must be reduced over the lifecycle of any given low-carbon power technology.

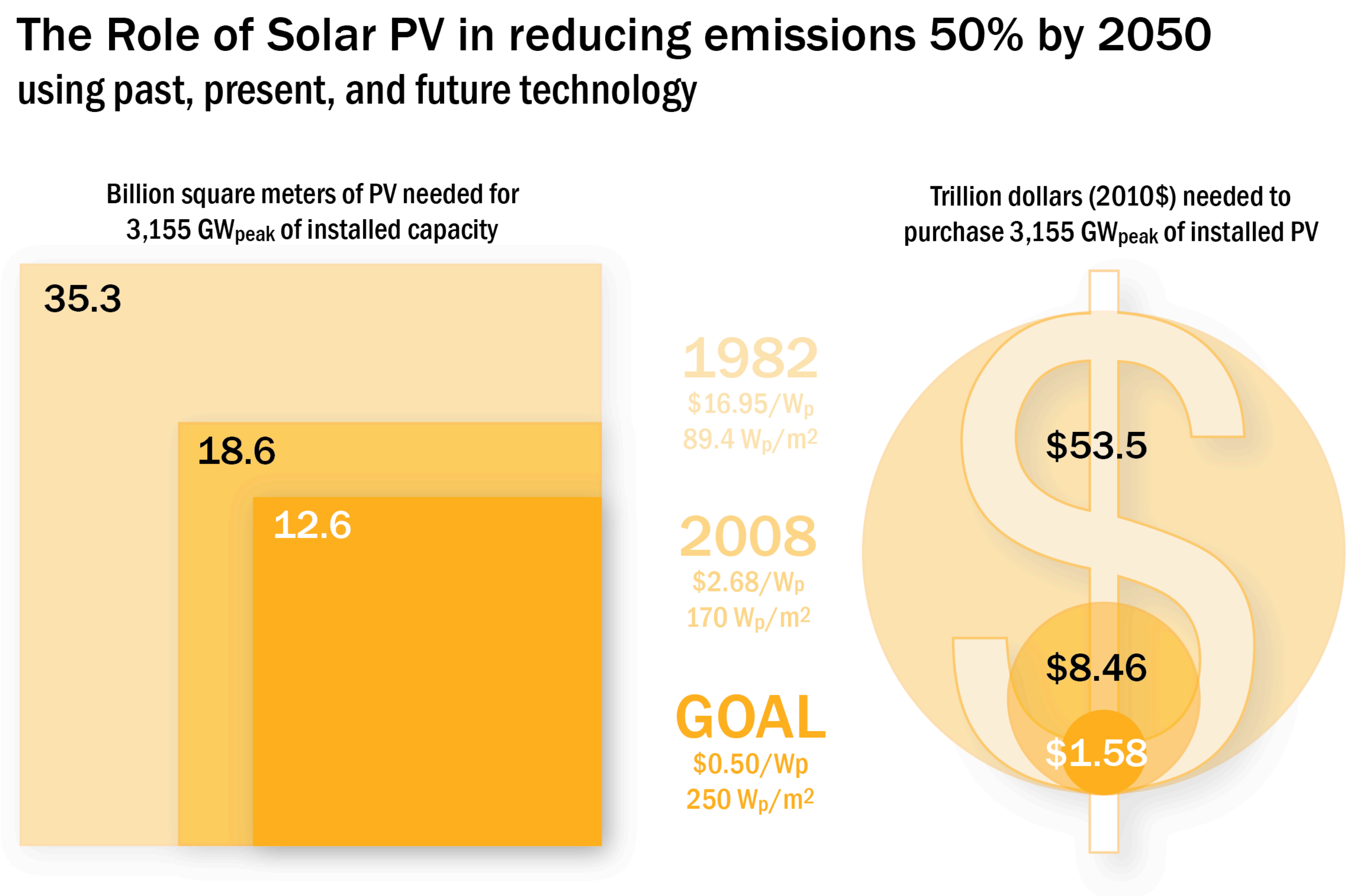
Environmental preservation has a temporal dimension: sustainability. One crucial element is the conservation of natural resources for future generations. Such natural resources can include biodiversity, energy and mineral resources, forests, and entire ecosystems (and the services they provide). **Innovation today is necessary to reduce the low-carbon power sector's environmental footprint to help ensure these natural resources are sustainably managed and available for future generations.**

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 Figure 1: Solar Panel Cost and Area Changes and Figure 2 Wind Turbine Cost and Scale Changes, successful innovations in materials, production processes, logistics, and other steps in the value chain underpin dramatic changes in cost and performance. The figures also highlight how low experts project innovation could drive costs in the future.

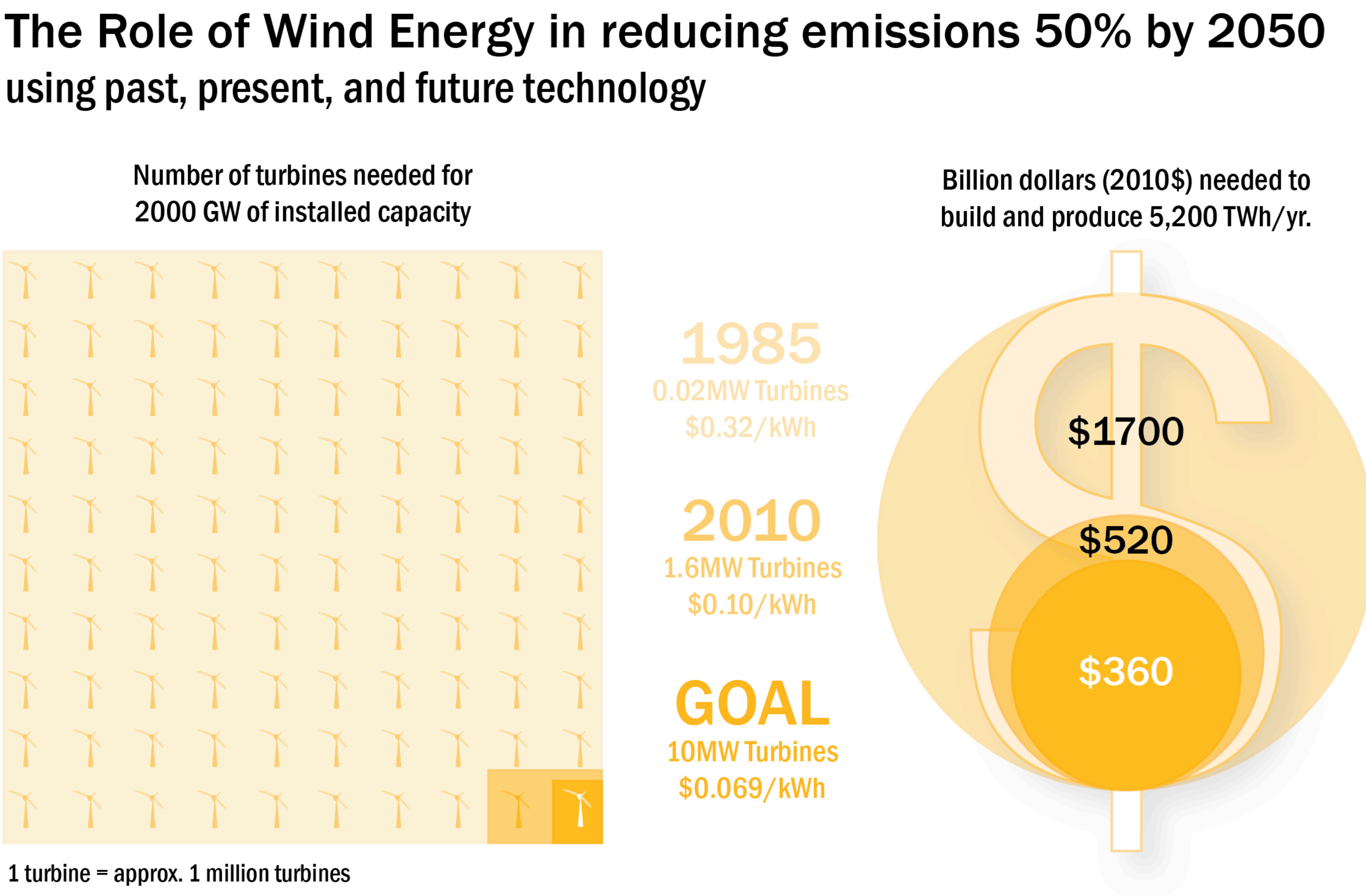
Innovation has not always happened at the breakneck pace seen in the twentieth century, and innovation in energy has often been painfully slow.[70] Nicholas Stern warns, **the cost of actions to mitigate climate change "will be higher if innovation in low-carbon technologies is slower than expected"**.[71] It should not be assumed that innovation would happen fast enough to address the urgent challenges without support from policymakers.

Figure 1 | Solar Panel Cost and Area Changes



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.[72]

Figure 2 | Wind Turbine Cost and Scale Changes



To achieve a 50 percent reduction in greenhouse gas emissions by 2050 (compared to 2005 levels) the IEA estimates that 2,000 GW of installed wind capacity will be required by 2050, enough to provide 12 percent of global electricity production. Over time, innovations have made reaching this target easier. Between 1985 and 2010, innovations like new materials and improved methods of production, including improvements through learning-by-doing and finding economies of scale, have made wind turbines more capable and their electricity cheaper. While many factors—such as commodity prices—also impact costs, future innovations can continue to improve wind turbines and farms pushing toward a competitive position in electricity markets, estimated to be US$.069/kWh levelized cost of electricity.[73]

SECTION 2—UNDERSTANDING INNOVATION

Our focus is accelerating innovations in the low-carbon power sector in order to drive down cost and improve performance as a strategy to achieve economic development, energy, and environmental goals. Section three provides a step-by-step process to do this, but **understanding what an innovation is and how it emerges is an important foundation**. There is more than thirty years of research into innovation-led economic development.[74] This literature, when blended with the extensive writing on the low-carbon power sector[75], can provide insights to strengthen an innovation strategy.

In this section we will define innovations, the processes that create them, and the ecosystems that support innovators in this sector. Armed with this, we will turn to how the low-carbon power sector works and how innovators can be effectively supported as an engine of economic growth.

Box 2 | 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.[76]

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.

Technological regime – the characteristics of the sector and technology that deeply shape how the innovation process unfolds.

Defining Innovation

Innovation is an exciting concept, evoking images of life-saving drugs or sleek cell phones. Despite innovation often meaning a physical thing—like a computer—academics agree that innovations can also be new ideas, practices, and organizations.[77] All innovations involve change but not all change is an innovation.[78]

An innovation in the low-carbon power sector is any change in a product, process, or policy that results in reduced cost or improved performance in the generation of low-carbon electricity.[79] An innovation is successful if it is adopted widely enough to impact the market.[80] This means innovations can be large, or quite small and incremental. When studied closely, most large or transformative innovations are composed of many smaller innovations and defining a clear difference in scale becomes very difficult.[81]

- **Product innovations** are new products or improvements in existing products. For example, changing the shape of the wind turbine blade or the material used to make it so that it is more efficient or lasts longer would be a product innovation.
- **Process innovations** are improvements in how products are made, sold, shipped, installed, operated, or maintained. Combined-cycle power generation is one example of a process innovation that captures waste heat from a gas turbine generator and reuses it to make steam, which in turn drives a steam turbine to generate additional electricity. More energy is extracted out of the same fuel inputs.[82]
- **Policy innovations** are improvements in the public policy environment or the organization of institutions. For example, creating a new agency and a streamlined procedure to handle siting requests for renewable energy installations is a policy innovation. Policy innovations in the low-carbon power sector may include changes in energy policy, financial policy, or industrial policy. Policy innovations might also emerge through changes in the rules of large institutions like the multilateral development banks.

The lines between these categories are not bright. For example, streamlining a siting procedure could be considered a process innovation rather than a policy innovation. The key is that innovations emerge throughout the value chain, and many people—from regulators to energy policymakers, from financiers to field technicians—are innovators every day.

Box 3 | Innovation beyond the Lab in Wind

When policymakers think of innovations, they often imagine university researchers studying advanced materials in a lab. In reality, successful innovations have many more sources.

The IEA's Wind Roadmap estimates wind power costs will decline by 23 percent for onshore and 38 percent for offshore wind energy between 2010 and 2050, in part due to successful innovations.[83] Policy innovations such as feed-in-tariffs or grid codes can reduce regulatory risk and in turn the cost of capital. The operations and maintenance (O&M) costs can be reduced through the design of individual components, the quality of production of parts like gearboxes, the sophistication of the spare parts supply chain, and maintenance best practices. Scientific research on blade aerodynamics can mean capturing more energy from wind resources. Operations best practices can also maximize power output in low wind situations.

Innovations in the electricity system will also be important to bring down the cost of wind power. Transmission infrastructure and electricity dispatching procedures could take better advantage of variable renewable energy resources. Improved weather forecasting would allow better hour-by-hour planning of the wind energy supply. Similarly, policy innovations in electricity markets could increase wind power's competitive position vis-à-vis traditional fossil sources.

How Do Innovations Emerge? The Innovation Process

Catalyzing the emergence and spread of new innovations in the low-carbon power sector depends on understanding how innovations are created. Often the process of creating new ideas, products, and practices is also called innovation.[84]

The innovation process is putting resources like capabilities, skills, knowledge, or new supplies together in a new way.[85] A successful innovation process is a matching process between these new configurations and the problem at hand, which may have many criteria to meet.[86] Efficient wind power requires a turbine blade that is light, strong, and cheap. In this case, the problem the innovation process tries to solve is to find the materials, physical shape, and manufacturing process that can create an optimal blade.

Many who study innovation in climate-related technology will recognize a linear model of the innovation process, beginning with basic science and ending with diffusion (see Figure 3: The Linear Innovation Process below). Some power sector innovations do begin with basic science and this model can be useful for considering issues like level of financing risk. The linear model also has shortcomings.[87]

There are three critical issues that this model does not address. **Innovation processes are complex and iterative, deeply uncertain, and heterogeneous.**

- Complexity - An innovation process can happen at any point in a product's lifecycle, from design through commercial operation practices. Any number of actors from a wide range of organizations may be involved in designing and testing a change. An individual innovation involves many feedback loops where new information leads to further changes in the solution.[88]
- Uncertainty - When innovators embark on an innovation process they cannot know:
    - what steps and which partners will be most productive,
    - how many problems will come up with their design,
    - what the innovation will be in the end,
    - whether all the supporting innovations—like advances in grid management to address variable renewable energy sources—will be in place in time[89],
    - whether or how the context, like regulation, might change,
    - and whether they can successfully meet all the market criteria.[90]
- Heterogeneity - Innovation processes may draw on, or even be instigated by new discoveries in the basic sciences as the linear model suggests, but they also may come from new supplies, new capabilities like high quality machining, or new information about customers.

These processes can also differ depending on the type of innovation (product, process, or policy), where they happen in the value chain (manufacturing, logistics, O&M, etc.), and who the innovator is and where he or she is located.[91]

There have been attempts to articulate models that better capture these issues (see Figure 4: The Iterative Innovation Process below).[92] 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 such as the fact that many innovations in energy do not begin with basic science. Instead of a declining role for policymakers as the process moves forward, this model represents innovation processes supported by an innovation ecosystem, in which, as discussed below, policymakers are very active participants.

Figure 3 | The Linear Innovation Process[93]

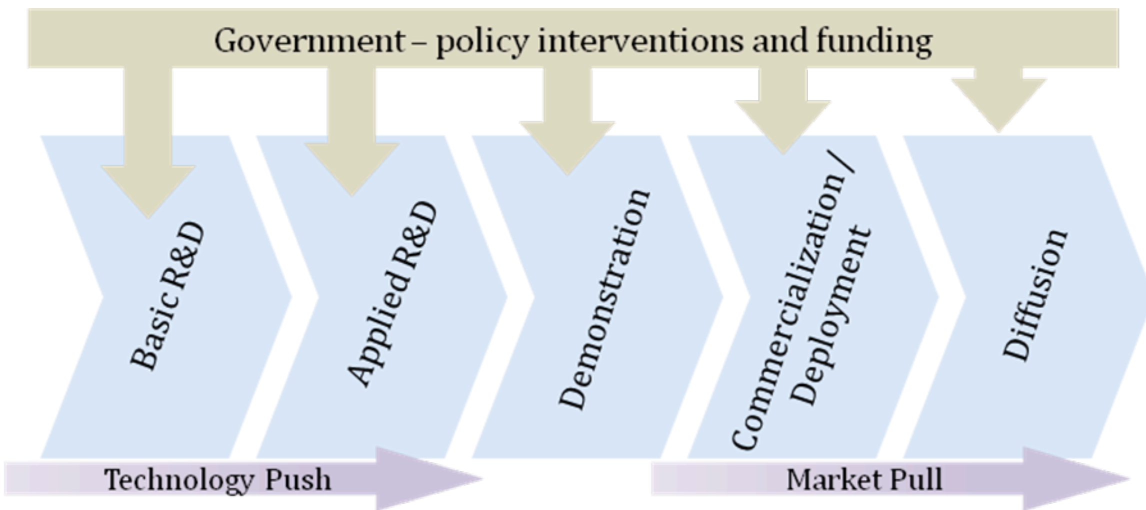
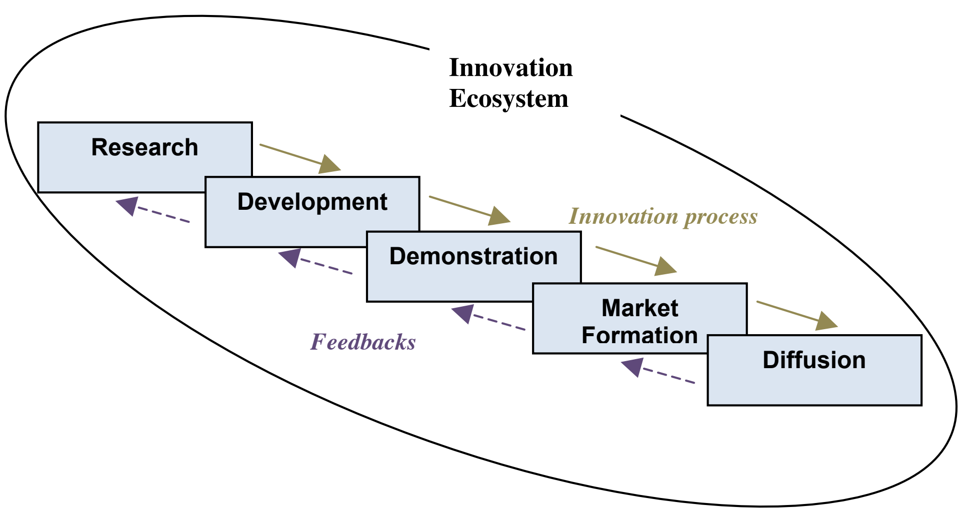


Figure 4 | The Iterative Innovation Process[94]



Taking the Systemic View: Innovation Ecosystems

What is an Innovation Ecosystem?

We have defined a successful innovation as a change in a process, product, or policy that brings down cost or improves performance and is adopted widely enough to impact the market. This is distinct from the innovation process; the way innovations are created and disseminated. A successful innovation process creates one or more successful innovations. But, innovation processes are very uncertain, heterogeneous, and complex. So how does a policymaker 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.

The innovation ecosystem is made up of the actors who participate in or support the innovation process and the rules that shape their interactions.[95] This is also called the innovation system in the academic literature.[96] The innovation process takes place in the context of the innovation ecosystem. Its chances of success are strongly shaped by how well that ecosystem supports innovators.[97] Every country and region has an innovation ecosystem already. Some are healthy and robust and innovators thrive. Others are weak or inefficient and innovators struggle to be successful.

The innovation ecosystem approach is unique.

- It assumes the ecosystem continues to evolve and change. The ecosystem is never 'finished' or in equilibrium.[98] This constant change comes from both external change such as the global economic downturn in 2008, and internal changes like the development of a new knowledge network.
- It focuses on learning. The participants are not rational actors with complete or nearly complete information. They are constantly learning and adapting.[99] Given the uncertainty inherent in the innovation process participants have bounded rationality, making the best decisions they can with limited information.
- It emphasizes that innovators need specific kinds of support but does not prescribe how to deliver those services. Many countries and companies are successful innovators while having radically different institutions and policies.[100]
- It includes market-based interactions, like those between an innovator and his customers or suppliers.[101] It also includes non-market interactions such as industrial associations and personal relationships, which have a profound impact on the innovation process and ecosystem.[102]

Innovation Ecosystem Functions

What functions does the ecosystem need to deliver effectively in order to increase an innovator's chance of success in the low-carbon power sector? While academics have not yet agreed on a list of necessary functions[103], we can build on their various approaches and create a list of the critical functions for this emerging sector. In Table 1: Innovation Ecosystem Functions in the Low-Carbon Power Sector each of these functions is illustrated by the plans outlined in India's Jawaharlal Nehru National Solar Mission, a mission to install 20GW of solar-powered electricity generation capacity by 2022.[104] It is too soon to evaluate the implementation of these plans, but they demonstrate an application of the innovation ecosystem approach.

The functions are interconnected and impact each other.[105] Creating new networks can contribute to creating markets. Creating markets can simplify the providing of finance. The functions are not abstractly 'delivered' by the ecosystem. The participants in the ecosystem and the rules that shape how they interact combine to implicitly deliver the functions.

Table 1 | Innovation Ecosystem Functions in the Low-Carbon Power Sector

Function	As Illustrated by India's Solar Mission[106]
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. It is insufficient to stop at the discovery step. Ensuring knowledge spreads effectively through the sector is also important. To do this, the thorny issues of intellectual property rights must be addressed so that knowledge is available but there is an incentive to continue to do research. There is also important non-competitive knowledge, such as electricity grid management procedures, which needs to be widely available to create a healthy ecosystem.[107] As new ideas in the low-carbon power sector are emerging in many countries, sharing of knowledge increasingly needs to happen internationally.	• Establishing a National Centre of Excellence (NCE) to implement the technology development plan formulated by the Solar Research Council. • Setting up of a network of Centers of Excellence—---located in research institutes, academic institutions, or even private-sector companies—each focusing on a research and development area of its proven competence and capability.
Building competence	
Skills in this sector are not easily learned from books and academic articles, but 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.	• Developing specialized courses in solar energy through collaboration with the Indian Institute of Technology (IIT) and premier engineering colleges. • Adopting a government fellowship program to train 100 selected engineers and scientists in solar energy in world-class institutions abroad.
Creating collaborative networks	
Networks are a fundamental tool for knowledge dissemination and creating the contacts innovators need to be successful. Even large, vertically integrated companies can rarely create an innovation alone. Innovation processes are more likely to succeed if innovators can quickly find a collaborator to provide the missing piece of their solution or help them discover a new approach to a problem. For instance, they need access to suppliers or to specialized services, such as solar resource characterization and electrical equipment certification. Exchanges in networks go beyond market transactions. Innovators find mentors and other non-market support in their networks crucial. Networks can be local, regional, national, or international in nature.	• Providing through the National Center of Excellence a national platform for networking among different centers of excellence and research institutions, including foreign R&D institutions and high-tech companies and multilateral programs. • Considering the creation of linkages with institutions like the Centre for Innovation, Incubation and Entrepreneurship to incubate solar energy start-ups and small and medium enterprises in India through mentoring, networking, and financial support

Function	As Illustrated by India's Solar Mission
Developing infrastructure	
Because individual low-carbon power 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.	• Encouraging state governments to establish solar generation parks with dedicated infrastructure. These would have power and water supply 24/7 and will ensure rapid access to imported raw materials and high-quality engineering talent.
Providing finance	
Innovators often need access to capital in order to realize their solutions, whether a new manufacturing process or a different wind farm configuration. Financing innovation activities is difficult because the uncertainty is high. This fundamental challenge can be exacerbated in countries with poor or non-existent capital or equity markets. A range of financial actors—public or private, domestic or international—with differing appetites for risk need to participate in order to create a healthy ecosystem that serves finance needs throughout the innovation process.	• Proposing to provide a soft refinance facility to create sustained interest within the banking community, for which the government will provide budgetary support. • Considering establishment of a fund to support at least 50 start-ups in solar technologies across India over the next 5 years. The Fund would provide financial (equity/debt) support to start-ups, entrepreneurs, and innovators for R&D and piloting of new solar technologies and for creating new and unique business models.
Establishing governance and the regulatory environment	
An innovation process is more likely to succeed when the rules of the game are clear and consistent. The innovator knows the bounds he must work within and the characteristics his solution must include. For example, if air or water pollution standards are clear, designing a new product or process and testing it will be simpler, even if the standards are stringent. Unclear standards add to the uncertainty that already complicates any innovation process. Governance and rules of the game can be considered in a very wide sense. Environmental standards, land use rules, the processes used to set tariffs and taxes, technical standards for connection to the electricity grid, financial regulation, and tax laws all shape the innovator's choices and options.	• Creating, in consultation with states, a single window clearance mechanism for all related permissions for doing business. • Ensuring the introduction of effective mechanisms for certification and rating of solar technology manufacturers. • Proactively implementing Special Incentive Package policies to promote photovoltaic (PV) manufacturing plants. • Recommending that solar components be covered under the Bureau of Energy Efficiency's star rating program to ensure high standards. • Considering custom and excise duties concessions or exemptions on specific capital equipment, critical materials, components, and project imports.
Creating markets	
The power sector is deeply regulated because the infrastructure forms a natural monopoly. As a result, policymakers have a strong hand in creating the market. There is a wide range of tools, from public awareness to	• Emphasizing Mission publicity and awareness campaigns. • Establishing a single-window, investor-friendly mechanism for the purchase of solar power for the grid, one that reduces risk and provides an attractive, predictable, and sufficiently extended tariff.

mandates to government procurement that policymakers can use to ensure there is a market for these innovations. Because this market is so regulated, the lines between this function and the governance and regulatory environment function are not bright. Policymakers often use a single tool, such as a renewable energy target, to improve the effectiveness of both of these functions. When working with this function, however, policymakers are explicitly creating a market for new innovations as opposed to more generally ensuring the rules of the game are clear.	• Making solar heaters mandatory, through building bylaws and incorporation into the National Building Code. • Announcing solar tariffs for rooftop PV applications. • Using a Renewable Purchase Obligation mandated for power utilities with a specific solar component.

Drawing Boundaries around the Innovation Ecosystem

One challenge of the innovation ecosystem approach is drawing boundaries around the system. These boundaries are somewhat artificial, but they provide a useful framework for analysis.

Geographic Boundaries

Within national borders, there is a common set of policies and a regulatory environment, a common language, and a shared culture that shape an identifiable and cohesive ecosystem.[108] The national innovation ecosystem (called a National Innovation System in the academic literature[109]) cuts across the economy and includes policies are that are not sector-specific, such as general incentives for research and development and support for higher education.

Since innovative companies tend to cluster in large metropolitan regions, sub-national regional institutions and rules can also shape innovation activities.[110] This can create geographic concentrations of innovation activities that are distinct from the national innovation ecosystem. In the academic literature this is called a Regional or Local Innovation System.[111]

For low-carbon power, particularly at the utility scale, national or regional circumstances can strongly shape the innovation process. For example, electricity production and delivery requires massive amounts of high-cost infrastructure, which creates a natural monopoly.[112] Significant government regulation is required to ensure quality of service at a reasonable cost and provide stability to the industry to support such large capital investments. Thus utility-scale power is highly regulated globally, even in markets where customers can choose their power provider. This means that national and sub-national regulations and regulatory bodies have a significant impact on the market, and as a result on the innovation process.

Sectoral Boundaries

Innovation ecosystems are not only shaped by their location, the characteristics of the concerned sector also matter. From this sectoral perspective, the technological regime—the characteristics of the technology itself—deeply shape the innovation process and as a result the ecosystem that supports it.[113] The technological regime strongly impacts the geographic dispersion of a sector, the competitive landscape, the types of networks and learning tools that may be most effective, and the best ways for innovators to derive profits from their innovations. This view of the innovation ecosystem has become known in the academic literature as a Sectoral Innovation System.[114]

In today’s globalized world, the low-carbon power sector's innovation ecosystem is international by nature. The involvement of multinational corporations has meant increased cross-border sharing of technologies and the knowledge surrounding them. A set of solar panels could easily be designed in one country, manufactured in another, and shipped to yet another country for installation. There are significant trade flows in the equipment and international investment in all parts of the value chain from research to project installation and operation.[115] Major manufacturers such as General Electric, Siemens, or Suzlon have research and development facilities in their home market in the United

States, Europe or India, but also beyond: General Electric has R&D centers in Latin America and Southeast Asia, Siemens' Corporate Technology is present in Beijing, Moscow, Bangalore, and Singapore, and Suzlon has strong R&D facilities in Europe.[116] Besides private actors, a number of international public-sector initiatives also shape the sectoral innovation system. There are many bilateral research partnerships between countries, as well as international organizations dedicated to the promotion of low-carbon power technologies, for example the International Renewable Energy Agency, or initiatives under the Clean Energy Ministerial. Public financial institutions such as the World Bank and development agencies are supporting low-carbon planning, enabling conditions for innovation and specific projects.

Innovating in the Low-Carbon Power Sector

Given the focus on low-carbon power, we will adopt the sectoral approach, which includes regional, national, and international elements. **The sectoral approach enables us to understand why and how innovation processes are different in the low-carbon power sector than in other sectors.** This in turn allows policymakers to realistically identify the opportunities the sector may offer for domestic economic growth and the most promising approaches to support innovators in this specific field.

Below, we discuss our analysis of how the technological regime shapes the innovation process in this sector. For a more detailed analysis, building on Breschi and Malerba's conception of the attributes and dimensions of a technological regime, see Appendix B: The Technological Regime of the Low-Carbon Power Sector.

Scale of Investments

In low-carbon power technologies, **large levels of investment are needed to make progress in research, and these investments are required in large sums at particular moments in time rather than evenly spread throughout the process**.[117] The necessary time horizons for earning benefits from that investment in research are also quite long as capital turnover in the industry is slow.[118] Newly constructed power plants have an expected operational lifetime of more than 30 years.[119]

Box 4 | Characteristics of the Low-carbon Power Sector

- Large investment needs
- Fierce competition
- Diverse sources of new knowledge: science, suppliers, customers, and others
- Knowledge is often tacit and/or effectively appropriated
- Many opportunities to innovate as the technologies are not yet mature
- Few new entrants and a relatively important role for large, global players
- Geographic clustering of innovators, often near customers.

Demonstrating a new solution also requires significant investments and time. For example, planning for an individual CCS demonstration project typically takes three to four years and can stretch out to a decade before construction can begin. The IEA estimates that each of the 38 CCS projects in the power sector included in its Technology Roadmap until 2020 would cost about $1.25 billion.[120]

Competitive Landscape

Electricity is a commodity delivered in a highly regulated market characterized by the natural monopoly formed by the grid. As most low-carbon electricity generation technologies are components of this larger energy system, **they face steep competition from highly subsidized and fully mature fossil fuel options from the moment they enter the marketplace**.[121] There is often no niche market with lower price pressure for these technologies to mature in. For instance, when a concentrating solar plant comes online it faces a highly price-sensitive transmission system that always buys the low-cost electricity first.[122]

The regulated nature of the industry can further dampen investment in innovation, particularly by utilities. Investment choices must often be justified to regulators who are setting the prices for energy in the marketplace. For example, major American utility American Electric Power (AEP) has decided to postpone a US$668 million project to capture carbon dioxide from an existing coal-burning power plant, in part because "they did not believe state regulators would let the company recover its costs by charging customers, thus leaving it no compelling regulatory or business reason to continue the program".[123]

In the absence of rules to favor low-carbon electricity, **low-carbon power sector technologies are essentially price takers and cannot charge a premium for the public benefits they offer**. In markets where innovators can charge a premium for their innovations, either because there is policy support for low-carbon solutions or because there are costs associated with using high-carbon solutions, there is larger opportunity to deploy innovations in a way that allows the innovator to make a profit.

Nature of the Knowledge

Knowledge in the low-carbon power sector is often highly tacit, complex, and part of a larger system. While the mechanical aspects of individual technologies may be codified in blueprints and scientific articles, how to effectively manufacture, site, and operate the equipment is highly dependent on tacit knowledge; that is, knowledge that cannot be easily communicated in writing and depends more on experience. Similarly, the knowledge required to integrate variable power sources like wind and solar into the larger grid is deeply dependent on an understanding of the specific grid, its fuel sources, its loads, and its technical capabilities.[124]

Knowledge in this sector flows from different sources. In the design phase, science and fellow innovators are an important source of knowledge, while suppliers and customers are key sources of new knowledge in later stages of the value chain.

Innovators in the low-power carbon sector have found a number of effective approaches to appropriate their knowledge; that is, to ensure that they can control their innovations in such a way that allows them to reap economic benefits. For tacit knowledge, tools like trade secrets, non-disclosure agreements, and employee retention programs are very effective.[125] For codified and more easily reproducible knowledge, intellectual property protection tools, in particular patents, are being used.[126] Some participants in the sector argue for stronger intellectual property regimes and effectively protect their knowledge by limiting its flow to foreign markets.[127]There have also been accusations that wind power companies use intellectual property rights (IPR) to limit competition in their domestic markets long beyond the point of usefulness in the larger drive for improved performance.[131]This points to the complex need to balance appropriability with knowledge spread that supports innovation (see Box 5: Balancing Intellectual Property Rights with Useful Knowledge Spillovers).

Policymakers can encourage the exchange of knowledge, particularly in those areas where shared knowledge isn't seen as a threat to the competitive position of innovators. Because this sector builds on so much tacit knowledge, **tools that encourage long-term relationship building, hands-on experience, and face-to-face interactions are critical**. Long-term collaborations applied to specific contexts, such as collaboration between energy regulators in developing countries or grid operators grappling with unique blends of electricity supply, are particularly effective.

Box 5 | Balancing Intellectual Property Rights with Useful Knowledge Spillovers

Intellectual property rights are a contentious issue in the low-carbon power sector. In the UNFCCC negotiations the issue is raised both by countries who want current agreements fully enforced,[128] and by those who want to remove existing protections.[129] Accusations of theft and unjust profiteering are subtly traded.

There are competing arguments about the optimal level of property rights protection. On the one hand, some economists argue that IPRs encourage innovation by allowing the innovation some level of appropriability: the ability to benefit from innovation activities. Other economists point out that this protection reduces competition, raises prices, and lowers diffusion.[130]

Striking the effective balance between encouraging innovation by ensuring appropriability and encouraging innovation by ensuring competition is very difficult. That balance is also likely to shift and change as the sector matures. It is also important to remember that a great deal of knowledge critical to innovation in this sector is non-competitive and thus there is significant room for cooperation and collaboration even if appropriability is being strongly protected.

China has shown that with strategies that explicitly address the high appropriability and high level of tacit knowledge, such as purchasing German wind design firms complete with the engineering staff, it is possible to enter this market and rapidly move into the top tier.[132] Another strategy could be to seek out niches in the value chain where a country may already have some of the necessary capabilities. This would leverage existing tacit knowledge to lower the overall investment and time needed to become expert.[133]

Industry Structure

There are significant opportunities for low-carbon power innovation, in the sense that searching for new solutions is very likely to create innovations. The ground is not as well covered as it might be in a mature sector like textile manufacturing.[134] However, the specific characteristics of this sector—high investment requirements, steep competition from fossil fuel sources, high degree of tacit knowledge, and of appropriability—make it more difficult to translate this innovation opportunity into economic opportunities. They also make it difficult for new entrants to be successful.

Nonetheless, **the high level of innovation opportunity leads to a rapid turnover in the hierarchy of established innovators**. For example, the ranking of the top ten solar or wind manufacturers changes year to year.[135] These rankings also reflect the fact that there can be successful new entrants, such as Suzlon, the Indian wind power manufacturer, or Yingli, the Chinese solar panel maker. These companies demonstrate that strategies that take the industrial structure into account can be very successful.

The low-carbon power sector tends to be dominated by a small group of large companies. For example, in 2010 the top ten wind turbine manufacturers controlled 79 percent of the market.[136] The investment needs and high degree of tacit knowledge discussed above explain some of this consolidation. Additionally, innovations in these technologies are highly cumulative; that is, the next innovation is closely related to the prior innovation. As a result of these characteristics, many companies are large global players.

The geographic distribution of innovators is different throughout the value chain because the sources of new knowledge change at each phase. In the design phase, the significant tacit knowledge and fact that most innovations build directly on other innovations lead to clusters of innovators around innovation resources, as found in wind power R&D around the NREL National Wind Testing Center.[137] However, suppliers and customers are another key source of new knowledge, particularly for manufacturing, services around project development, and O&M. As a result, innovators in later stages of the value chain are clustered near large customer groups. The size of some of the technologies—such as turbine blades—also drives innovators to be close to customers.[138]

This global/local pattern can limit the actual distance between the clusters of innovators by creating well-integrated, small communities of practice. This in turn makes collaboration and knowledge transmission easier. It also presents opportunities for local or regional entrants if they can effectively join the international community of practice and begin to master the necessary knowledge. There may be local niches that a local player can excel at and the existing international links could then provide easier access to export markets, though this pattern also creates stiff competition for new entrants.

Understanding the different patterns of clustering is important for new entrants. Creating an R&D cluster will require a different strategy than building a manufacturing or services cluster would. Smaller countries or sub-national regions may in particular want to look beyond their borders for large customer groups.

A New Role for Policymakers

The innovation ecosystem approach suggests a new role for the policymaker as the catalyst and organizer of resilient, dynamic, and adaptive innovation ecosystems.[139] Policymakers are a part of the system, fulfilling some of the needed functions such as forming new markets or setting rules. Policymakers can also remove some of the debris that chokes less productive ecosystems. **They need to identify and resolve failures in the innovation ecosystem functions, which may be market failures or other barriers to successful innovation processes.**[140] The framework in section three is a step-by-step guide to do just that.

SECTION 3—BUILDING A DYNAMIC INNOVATION ECOSYSTEM

As national and regional policymakers build a dynamic ecosystem, there is a range **of policy tools available to promote innovation**. For example, public investment in R&D can induce innovation in low-carbon power generation, as can market-creation 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**. The framework includes the steps summarized in Table 2: Steps to Build a Dynamic Innovation Ecosystem.

An effective framework for action is built on a high degree of communication and collaboration among ministries and other national and sub-national government agencies, as well as stakeholders outside government, including the private sector, universities, and civil society. These stakeholders need to work together to craft a policy package that responds to local social, economic, environmental, and technological conditions, as there is no one-size-fits-all policy prescription for accelerating innovation.

STEP 1: Global Value Chain Assessment and Positioning

Landscape Assessment

The low-carbon power sector includes a heterogeneous set of electricity generating technologies stretching from equipment manufacturing to electricity production and integration with the grid. **It is critical to determine which part of this global low-carbon value chain and which technologies to focus on, in order to most effectively nurture the innovation ecosystem.**

A landscape assessment can quickly become a complex undertaking, so it is necessary to organize this analysis and the information derived from it in a systematic way. Although different procedures will lead to similar results (provided they are thorough), an effective way to structure the assessment is to investigate each of the points in Table 3: Landscape Assessment—Areas for Data Collection.

Table 2 | 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.

Table 3 | 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.
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.

	What to assess	Why is this relevant?
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.

It is important to ensure that the first part of the assessment—the context of the country—is analyzed with the low-carbon technology value chain in mind. The second part of the assessment, which is technology-specific, should be done separately for each technology under consideration and for each potential entry point in that technology's value chain.

Context of the country or region

The first part of the assessment focuses on the assets, capabilities, and contexts in the country or region. These are the general environment, the building blocks, and the challenges, which will shape the low-carbon power sector innovation ecosystem.

Underlying Characteristics

Underlying characteristics are relatively stable features of the country or region that significantly influence the scope of choices and policy strategies available.

What to assess: Relevant geographic features and natural resource endowments.

Why is this relevant?

Physical aspects such as geographic features and domestic resource endowment are critical determinants of the strategies available to the country or region. Some regions may have significant wind or solar resources, while others may have significant stocks of biomass. Fossil fuel reserves are also important, as they can influence the way low-carbon technologies are evaluated. Geographic characteristics influence the pattern of development and may dictate other constraints such as availability of water or land resources needed to deploy specific technologies. The local climate will also be more conducive to some technologies than others. When considering manufacturing, supplies of raw materials are also important.

Examples

- The supply of 'rare earths'—minerals that are crucial for the manufacturing of clean energy technologies such as compact fluorescent light bulbs, electric cars, and wind turbines[141]—is currently dominated by China, but other countries have the resource base to create a domestic supply.
- India's decision to embark on its National Solar Mission was in part arrived to through an assessment of its natural resources. Though, India also identified the monsoon season as a natural resource constraint for the domestic solar industry.[142]
- Both Indonesia and the Philippines have set themselves ambitious targets to rapidly expand geothermal electricity generation, reflecting a specific resource endowment in these archipelago countries located on the Pacific Ring of Fire.[143]

What to assess: Social aspects, including both social characteristics such as prevailing languages, social attitudes, and relevant cultural traits, and human capital variables such as education levels, population size, and demographic composition.

Why is this relevant?

Social characteristics will influence the way that economic actors will interact with each other domestically and internationally, some of whom may not share the same language or cultural values and customs. These characteristics can change over time, but such change is usually slow and not easily influenced by policy.

The more flexible human capital variables, such as education level, will shape the capacity to innovate by creating and using new knowledge. Other human capital variables, such as population size and composition, will also influence which niches and technologies will be most suitable to pursue, based on the intensity and type of labor needed.

Examples

- India was able to capture a good portion of outsourcing needs from English-speaking countries partly due to the fact that it shares the same language.[144]
- In China, personal relationships are key to business and social interactions; these form an important part of how information is exchanged, shaping the way networks and governance structures are established.[145]

What to assess: Political system characteristics and the current political landscape, including prevailing political cycles and structures, and existing political commitments and priorities.

Why is this relevant?

Decision-making processes may rule out some kinds of policy tools. Current political trends will also have a very strong influence on the available options. Existing political commitments could pose restrictions or create opportunities. Finally, the budget available to promote innovation must be considered.

Examples

- Transmission in the United States and European countries is operated in a decentralized way, limiting the power of federal policymakers to incorporate more renewable energy options.[146]
- Brazil's military regime in the 1970s prized strong national independence, and proved to be an ideal political environment to kick-start a government-funded biofuels

program along with mandatory ethanol blending in gasoline.[147]

- By 2011, the governments of at least 98 countries had set renewable energy deployment targets for their countries.[148]

Current Economic Activity

Existing economic activity include the trade flows, existing industries, and other production elements in a country that will influence and interact with the low-carbon power sector.

What to assess: Domestic production structures encompass all aspects of how the economy is organized to transform raw materials and other inputs into finished goods and services. This includes the quality and breadth of the underlying infrastructure and other public goods; the financial system's health, sophistication, and ability to fund economic activity; the institutions underpinning the smooth functioning of the economy, from the legal system to standard business practices; and the networks established between public and private economic agents.

Why is this relevant?

These factors will determine the strength and ability of the domestic economy to produce goods and services competitively, and to operate in international markets through trade and participation in trans-national value chains. These economic structures can be a source of competitive advantage.

Example

Strong commercial ties between Southeast Asian countries allowed different countries to focus on specific parts of the electronic industry that gained root in the region since the 1970s, bringing efficiency gains and emerging production practices like "just in time" inventory management and turn-key operations that heavily influenced other sectors.[149]

What to assess: Trade patterns arising from the goods and services already produced competitively.

Why is this relevant?

An economy that is efficient and competitive in a specific sector will likely be active in international trade as an exporter of a given tradable good or service.[150] Examining the existing patterns of international trade can reveal important insights about the capabilities of the local economy, as well as about the existing links between local economic agents and those in other countries and regions. Pursuing those niches in the low-carbon power sector that lend themselves to existing local capacity will require less effort and potentially less risk.

Example

China's meteoric growth in manufacturing exports in recent decades clearly revealed strong comparative advantages stemming from low labor costs and strong incentives as part of aggressive industrial policy. This comparative advantage spread out from low-grade manufacturing sectors like toys to more sophisticated products such as cars, computers, and other electronic devices and components.[151]

What to assess: Capabilities arising from the current production and trade portfolio.

Why is this relevant?

Engaging in the low-carbon power sector requires specific skills that may or may not be already present in the local economy, in the right places, and in the correct configuration for success. Because the knowledge in this sector is highly cumulative and tacit, it is important to consider existing technical capabilities and what they imply for absorptive capacity. How can the low-carbon power sector make use of knowledge and human capacity from other developed industries?

Example

Expertise for the design of wind turbine gearboxes can be derived from aerospace gearbox and automobile transmission technologies, if those sectors exist in the local economy.[152]

What to assess: Macroeconomic and financial trends.

Why is this relevant?

Both the domestic and international economic environments will have strong influence in a sector that is global by nature, and will shape the inputs and processes available to innovators to pursue innovative products and services in the relevant market niche.

Example

The global financial crisis in 2008-2010 hindered the development of many low-carbon technologies due to a lack of funding and negative forecasts about future economic growth. CCS is an illustrative example: by 2011, several planned projects were canceled, including a flagship CCS demonstration project in advanced stages, located in West Virginia in AEP's Mountaineer coal plant.[153]

Energy Supply

The energy supply is part of economic activity but should be scrutinized in deeper detail, as it will significantly influence the context in which low-carbon power technologies and innovations will be pursued. The energy supply context includes both the current and future sources of power in a country, as well as demand for power and future electricity price trends.

What to assess: Current energy provision setup, including fuel mix, fuel supply chains, costs, and demand, as well as medium-term forecasts of all these variables.
Why is this relevant?
The way energy is produced and transmitted today has a significant impact on how new low-carbon power generation technologies will emerge and operate. It is important to understand factors such as the current players in each segment of the sector, how each component of the energy mix is evolving over time, and how the prevailing regulatory framework impacts innovators operating specifically in the energy sector.
Example
Policy and regulation on how transmission operators choose between power generators can make it difficult for variable renewable energy generators to sell their power. Even when renewable energy is given priority in the system, the need to keep the grid stable and the existing fuel mix can together limit how much variable power can be used.[154]

What to assess: Current and future dependence on foreign sources of energy or other bottlenecks, and impacts on the political system.
Why is this relevant?
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.
Examples
- India's investment in solar power was in part founded on an anticipation of future fossil fuel constraints: "The situation will also change, as the country moves toward imported coal to meet its energy demand. The price of power will have to factor in the availability of coal in international markets and the cost of developing import infrastructure. It is also evident that as the cost of environmental degradation is factored into the mining of coal, as it must, the price of this raw material will increase."[155]
- Brazil's biofuels program started in the 1970s as a policy response in a time where energy security gained prominence in the aftermath of the international oil shocks.[156]

Environmental Considerations

Environmental considerations include the impacts of both high-carbon and low-carbon energy solutions.

What to assess: Current and expected pressures on natural systems from human activity.
Why is this relevant?
Impacts from high-carbon power, such as poor air quality and environmental degradation from coal mining, may add to the support for a switch to low-carbon technologies. However, new low-carbon power technologies include their own pressures on natural resources and ecosystems. These pressures need to be understood to avoid replacing one environmental problem with another.
As climate changes begin to emerge, there will also be changes to the natural resource endowment that will impact the energy infrastructure.
Examples
- Hydroelectric power generation will be impacted by changes in rainfall and snow regimes as a result of climate change.[157]
- Water requirements by some solar technologies can add pressure to already overstretched water systems.[158]

What to assess: Future domestic commitments to sustainability.

Why is this relevant?

Commitments made by politicians to pursue specific environmental outcomes, such as a pledge to limit greenhouse gas emissions by a certain amount over a specific timeframe, may help muster the political will and investment needed to adopt new low-carbon technologies. On the other hand, the absence of political appetite to pursue such outcomes may make it harder to put specific incentives in place.

Example

Maldives seeks to become the first carbon-neutral country in the world, a goal President Nasheed seeks to achieve by swapping fossil fuels for wind and solar power.[159]

International Cooperation

In this global sector, international cooperation and international technology networks are critical to successful innovation.

What to assess: The international technology cooperation landscape and current participation in these efforts.

Why is this relevant?

Climate change is a global concern and there are many ongoing global and regional attempts to address the dual issues of mitigation and adaptation. A country's involvement in internationally binding commitments, bilateral partnerships, and international organizations can contribute to a successful innovation ecosystem. Domestic policies may also urge or restrict international involvement. Current international commitments and involvement in international organizations may shape future decisions and have the potential to feed back into domestic policies. Strategic partnerships with other nations may also guide policy decisions.

Examples

- The IEA supports the creation and spread of clean energy technologies though its Directorate of Sustainable Energy Policy and Technology. The Agency has led technology R&D and international collaboration workshops in a number of large developing countries.[160]
- In 2009, the International Renewable Energy Agency (IRENA) became the first intergovernmental organization solely devoted to the promotion of renewable energy. One hundred and forty eight states and the European Union have signed the Statute of the Agency, mandating IRENA to facilitate access to relevant data and to share experiences and best practices on renewable energy.[161]
- The Clean Energy Ministerial (CEM) incorporates a number of international initiatives aimed at advancing clean energy technologies and their deployment. Twenty-two countries and the European Union, representing 80 percent of global energy consumption, participate in the CEM. CEM's Clean Energy Solutions Center aims to be a storehouse of information for policymakers designing and adopting programs and policies to support the deployment of low-carbon technologies.[162]
- Bilateral cooperation efforts have the potential to pool financial resources and knowledge from different countries in order to stimulate research programs. The US$150 million US-China Clean Energy Research Center (CERC)[163] and the US$25 million US-India Partnership to Advance Clean Energy (PACE)[164] are two significant centers directly funding R&D efforts.

What to assess: The availability of development assistance and international climate finance to support low-carbon power innovation ecosystems.

Why is this relevant?

This area is of particular importance to developing countries that often lack the financial resources for public investments in the innovation ecosystem. With the commitment made by developed countries in the context of the UNFCCC negotiations to mobilize US$100 billion a year by 2020 to address the mitigation and adaption needs of developing countries, there is a large opportunity for developing countries to access additional resources for innovation ecosystems.[165] Beyond dedicated climate finance, there are many initiatives to support climate change mitigation, energy sector development, or innovation as part of development cooperation, which could also be leveraged.

Examples

- The U.S. Government has launched an initiative on "Enhancing Capacity for Low Emission Development Strategies (EC-LEDS)", which will "support developing countries' efforts to pursue long-term, transformative development and accelerate sustainable, climate-resilient

Box 6 | Supporting International Collaboration through the UNFCCC Technology Mechanism

The United Nations Framework Convention on Climate Change (UNFCCC) represents climate cooperation at its widest breadth with participants from 194 states involved in climate negotiations. The Convention states that all member parties shall "promote and cooperate in the development, application and diffusion, including transfer, of technologies, practices and processes that control, reduce or prevent anthropogenic emissions of greenhouse gases."[166] At the 2010 Conference of the Parties (COP 16) in Cancun, member countries agreed to create a new Technology Mechanism, in order to enhance action on the development and transfer of technologies that support the adaptation to, and mitigation of, climate change.[167]

This new mechanism will consist of two new institutions: the Technology Executive Committee (TEC) and the Climate Technology Centre and Network (CTCN). The TEC is a group of 20 experts tasked with identifying technology needs, coordinating international efforts, and developing recommendations to make technology policy more effective. The CTCN is designed to bring together national, regional, sectoral, and international technology networks and relevant organizations and initiatives.
It will provide technical assistance and training to countries and create tools and policies that directly support the innovation and diffusion of low-carbon technologies.[168] It is unclear specifically how the two components of the Mechanism will work. Where the center will be, what the network will look like, and how they will operate and interact are just some of the questions to be answered.

The new Mechanism could provide support to countries willing to invest in low-carbon innovation and could strengthen the international innovation ecosystem if negotiators are successful in resolving these questions. The Technology Mechanism will be particularly well positioned to support the developing world. The CTCN can deliver much needed capacity building by helping policymakers identify their country's needs, providing tools and experts, and helping policymakers arrive at country specific solutions to their unique needs.

It will be crucial to the Technology Mechanism's success to clarify how its activities are linked to the access to finance. A lack of access to finance is frequently identified as one of the most significant barriers to technology development and deployment by developing countries.[169] Several proposals have been made to link the activities promoted by the Technology Mechanism to the Green Climate Fund that was also created in Cancun. At a minimum, CTCN could be equipped to assist developing countries in drafting project proposals, identifying sources of public funding and private investment, and attracting those finances with proposals that have the "stamp of approval" of the CTCN.

As the Technology Mechanism is developed further, country negotiators have the opportunity to shape its future and ensure the Mechanism is designed to fit their country's needs.

economic growth while slowing the growth of greenhouse gas emissions." The initiative provides capacity building, technical assistance, and a shared international knowledge platform. If the partner countries in this initiative see improving low-carbon power innovation ecosystems as a component of a low-carbon development strategy, they can use these resources to plan and implement their policy interventions.[170]

- The Government of Norway is planning a new "Energy+" partnership "to promote access to energy and low-carbon development" through renewable energies. This multi-billion dollar initiative would involve several donor countries and the private sector and could become a major source of finance for transformative energy innovation activities in developing countries.[171]

Factors related to each technology under consideration

The second phase of the assessment addresses the specific technologies that a country or region may choose to pursue, and the opportunities within those value chains. These opportunities will interact with the local context analyzed in the first part of the landscape assessment. Applying the analysis of the low-carbon power sector above (Innovating in the Low-Carbon Power Sector) may also be useful in this step.

What to assess: Technology characteristics.
Why is this relevant?
Each technology has characteristics that make it more or less attractive in a given context. These include the technical aspects of generating energy through a specific process, but also include the existing or emerging value chain associated with the technology. The various components and processes required to deliver energy through each existing major technological pathway are different. One country or region

may be better equipped to take part in one over another. The assessment above of existing capabilities should be directly compared to the requirements of pursuing each technology pathway.

Example

India's design and focus of its National Solar Mission is in part based on an assessment of its existing technological capabilities: "The Mission in its first two phases will promote solar heating systems, which are already using proven technology and are commercially viable. […] Indigenous manufacturing of low temperature solar collectors is already available."[172]

What to assess: Value chain characteristics.

Why is this relevant?

The characteristics of the global value chain for each technology will be critical in deciding which technological pathway to pursue and the best way to do so. Some segments of the value chain will be easier to localize and retain than others. Some require deeper science expertise while others favor labor-intensive manufacturing. Some require responsive customer service and others operate at arms length.

Example

Portions of the wind power supply chain, particularly the production of towers and the large turbine blades tend to locate near the customers. In 2008 the Chinese government began planning for seven "GW-scale wind power bases." As a result, China's wind turbine equipment manufacturing industry has developed rapidly in recent years, and manufacturing plants are particularly concentrated in the vicinity of these power bases.[173]

What to assess: International competition and interactions.

Why is this relevant?

There are high barriers to entry and very strong international price competition in most energy technologies. Innovation policy is not created in isolation, but partly in response to policies elsewhere.

Example

China has invested significant efforts to build highly competitive industries in wind and solar photovoltaic technologies, and made deep investments in the innovation systems to support those industries.[174] Choosing to compete directly with Chinese firms on the same products may be difficult, but there may be niches, regional markets, or location-constrained parts of the value chain that do not face the same competitive pressure.

What to assess: Existing relationships with international investors, innovators, and supply chain partners.

Why is this relevant?

Interaction in an innovation system does not just occur through competition, but also via transactions with suppliers and customers and via public sector networking. These existing relationships will also help determine the best technology or value chain segment to pursue. Transfer of technology commonly occurs through four routes: trade in goods, foreign direct investment, trade in knowledge (licensing), and movement of people.[175] This breakdown is useful for considering the assets a region or nation might consider in the low-carbon power sector. Do multinationals with low-carbon power technology portfolios already invest in the region? Is there a flow of human capacity between the domestic industry and clusters of expertise elsewhere? These networks take years to develop,[176] so existing networks should be highly valued.

Example

Brazil and Mozambique have fruitful cooperation on biofuels, conservation agriculture, and renewable energy policy.[177]

Concluding the Landscape Assessment

The final step in conducting the landscape assessment is to integrate the two sections. Examine the specific characteristics of the country or region and the international environment in the context of each potential entry point in the low-carbon technology value chain. Viewed under this light, each of the national characteristics will become a strength or weakness, and inform opportunities and threats.

The landscape assessment will suggest areas where a nation or region will have the best chance to succeed in entering the low-carbon power sector. However, there is always a risk that a strategy will put a country onto a dead-end path. It is unrealistic to assume that any such assessment will guarantee the correct decision, particularly considering that the global environment is in constant flux. For this reason, it is best to view the landscape assessment as an ongoing practice, providing information on the best way to adapt and create new policies over time. Succeeding in this emerging and yet highly competitive sector requires flexibility. Consider how to best blend assets and resources together in new and more competitive ways to be continually relevant in a quickly evolving environment.

Goal Setting

Goal setting will result in focusing a nation or a region on one or more segments of the low-carbon power sector value chain and on one or more specific technologies.

Sometimes, the goal is already set. India, for example, has decided to focus on its domestic solar industry. As part of its National Solar Mission, it has set a target of 20GW of solar powered electricity generation capacity by 2022.[178] This goal is paired with that of achieving grid parity by this same date, thus linking to all-important cost criteria. India has also set specific targets for the share of renewable sources such as wind, hydro, biomass, and solar in electricity generation for each of its national five year plans through 2022. In this case, the landscape assessment can inform how to best achieve the goals, and future updates of the goals.

Goals in the low-carbon power sector, in turn, contribute to achieving the broader economic development, energy, and environment goals, by narrowing in on the best opportunities for innovation-led economic development. In China, for example, policymakers have set goals for the low-carbon power sector to improve wind turbine quality in order to meet international standards and create an export market, which in turn will contribute to economic development.[179] Renewable energy policies currently under consideration in South Africa are explicitly tied to a number of economic development objectives: "Industrial development … in the industrial value chain supplying the [renewables] industry," "export competitiveness," "regional renewables development … to be a regional hub and catalyst for the development of renewables in sub-Saharan Africa," "medium-term energy security," and catalyzing the "conditions for green growth."[180]

Box 7 | Summary of the Low-Carbon Innovation Ecosystem Functions

- Creating and sharing knowledge
- Building competence
- Creating collaborative networks
- Developing infrastructure
- Providing finance
- Establishing governance and the regulatory environment
- Creating markets

STEP 2: Ecosystem Analysis

The next step in building a dynamic innovation ecosystem is to analyze how well the system is functioning today, in a given place, for a given technology. What about the innovation ecosystem is working and what is not? In a spectrum that runs from non-existent, or weak, functions to well-established, robust innovation ecosystem functions, **where are interventions necessary to improve their efficiency and effectiveness?**

To determine this, it is essential to:

- Make use of data and findings derived from the landscape assessment.
- Consider the results that the functions are meant to achieve, rather than focusing on how a function should be implemented. There are many tools that can be implemented to improve how effectively a function is delivered. These will be explored in step three.
- Analyze the innovation ecosystem functions within the context of the chosen technology and segment of the low-carbon power value chain identified in step one of the framework.

It is critical in this review to consult with low-carbon power sector stakeholders—from investors to end consumers—to identify where they need additional support and create policy that is both effective and politically sustainable.[181] This is partly because the users of the current system are the best placed to identify the shortfalls but it is also simply a matter of good governance.

This step should produce a good understanding of the current performance of the innovation ecosystem. This includes an understanding of the functional failures and gaps that may be choking innovation processes in the target technology. It also includes an understanding of where effective functions could be enhanced to amplify their impact. This analysis builds on step one, where the choice of a target technology is built on a nation's or region's existing strengths and capacities. However, **the results of this analysis are more detailed than in step one, since the ability to focus on a specific technology narrows the scope**.

Analyzing Innovation Ecosystem Functions

Creating and sharing new knowledge

Research and development is critical to innovation. For new knowledge to be created, it is necessary to effectively support research institutions and technology demonstration projects. Much of the critical new knowledge may not be scientific, so it is important to understand all of the existing knowledge gaps innovators face, and support many types of knowledge creation.

For example, in support of the goal of manufacturing the next generation of wind turbine blades in the United States, particularly those larger than 50 meters, the U.S. Department of Energy (DOE) recently announced a plan to fund the creation of a Wind Technology Testing Center in Massachusetts.[182] Once completed, this facility will allow the U.S.-based wind sector to acquire new knowledge currently only derived from similar testing facilities in Europe. The Wind Technology Testing Center will provide new knowledge about the structural integrity and durability of blades of up to 90 meters long.[183]

Illustrative questions:

- Does the country or region have thriving institutions to generate new knowledge?
- Are government and private sector R&D budgets growing, stagnating, or declining?
- Have the key stakeholders most likely to generate new knowledge—the scientists or technical experts from academia, research, and private sector institutions—been identified?

Not only is new knowledge generation necessary, but also so is usage and dissemination of this knowledge. New knowledge is of little value if it cannot be incorporated to improve products, processes, or services. For some of this knowledge, there has to be a legal framework in place to protect intellectual property rights while simultaneously promoting collaboration and information dissemination.[184] Valuable, non-competitive knowledge such as the mapping of domestic renewable resources should be disseminated through every possible means.

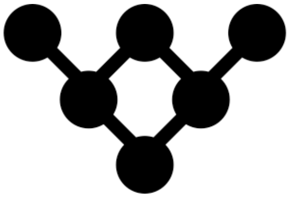
Building competence

A competent labor force is a key driver of innovation. Not only should the workforce be educated and well trained, but also it must be flexible to adapt to changing technological trends. It is important that a country or region be a magnet for intellectual capital, rather than a source of brain drain. India for example, as part of its National Solar Mission, has set out to adopt a fellowship program to place 100 scientists in world-class institutions abroad to acquire knowledge and apply it back to their domestic solar industry.[185]

Illustrative questions:

- If a country has chosen to develop its biomass-powered generation capacity, is the education system graduating a sufficient supply of candidates with advanced degrees in biological and agricultural engineering?
- Are educational institutions well funded to attract intellectual capital and send students overseas to gain international exposure?

In this sector, important competencies are not acquired through textbooks or academic institutions but rather through practice and applied technical institutes. If the goal is to deploy rooftop photovoltaic panels on every home, then industry training facilities for individuals to become certified as professional solar panel installers may be key.[186] If the goal is to build large offshore wind farms, then the workforce must be able to acquire the necessary safety training to work atop giant wind turbines.[187] Just like academic institutions must be well resourced to attract global talent, training facilities should be well equipped to train professionals in the latest technologies.



Creating collaborative networks

Innovation feeds on collaboration and cannot succeed within closed walls. A healthy innovation ecosystem is one that promotes the creation of collaborative networks for the flow or exchange of information, products, and services. Collaborative networks allow private-sector companies, research institutes, academic institutions, civil society, and government to all learn from each other.

A recent example is the U.S.-China Clean Energy Research Center (CERC).[188] Announced in November 2009, CERC specifically aims to promote "collaborating to advance clean energy technologies by building upon their ongoing scientific and technological cooperation in this area among research institutes, universities and companies."[189] CERC leverages both public and private funding to support joint research efforts on advanced coal technologies, clean vehicles, and energy efficient buildings.

Collaborative relationships are also necessary as part of a product supply chain. Product networks allow firms to determine what they need to produce at home versus what they can obtain from someone else. For example, the U.S. Photovoltaic Manufacturing Consortium was recently established as a collaboration between SEMATECH, an international semiconductor manufacturing consortium, and the College of Nanoscale Science and Engineering at the State University of New York at Albany.[190] This consortium is actively emphasizing the "importance of a collaborative supply chain."[191]

Innovators also benefit from networks of peers and role models. These non-market based relationships are crucial to problem solving, accessing new information, and coping with the uncertainty inherent in innovation processes.[192]

In evaluating how effectively the innovation ecosystem is providing opportunities to collaborate, the analysis from step one on existing networks will be useful.

Illustrative questions:

- Are there formal and informal networks that support collaboration?
- Do low-carbon power innovators have contacts in key companies and universities?
- Do they attend the important international conferences in their field?
- What joint research is underway already?
- Where could new initiatives be useful?
- Are there domestic, regional, or international collaborations that might be useful?

According to the OECD, governments should not, however, attempt to be the main architects of networks but rather incentivize their self-organization, providing mainly management, administrative, and organizational support.[193]

Developing infrastructure

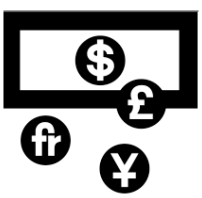
The low-carbon power sector cannot thrive without appropriate public infrastructure: efficient marine ports and airports, a reliable electricity grid, high-speed telecommunications networks, good roads, available water supplies, etc. Public infrastructure development must match the specific needs of the technology that a country or region has chosen to embark on.

Illustrative questions:

- If the choice is to develop a solar industry, do solar manufacturing firms have access to good roads so that high-cost imported and exported products arrive in one piece?
- If the goal is to develop the wind industry, does the country have large trucks and cranes to transport and install utility-scale onshore wind turbines?
- What about marine vessels to transport wind turbine components, drill the ocean floor, and erect offshore wind turbines?

- If a country is in a position to mass manufacture solar panels to meet global demand for cheap panels, do manufacturing plants have 24/7 dedicated power, or are production lines at the mercy of frequent power outages?

One way to provide infrastructure support to the low-carbon power sector is to upgrade existing infrastructure to facilitate the transportation of renewable energy goods. For example, in October 2010, the UK government allocated £60 million to "upgrade harbour infrastructure to support the rollout of offshore wind farms", which prompted wind turbine manufacturer Gamesa to announce their location of a new factory in the UK.[194] In November 2010, Scotland followed this approach by launching a National Renewables Infrastructure Fund with the goal of "boosting port and manufacturing facilities, supply chains to manufacture offshore wind turbines and related parts."[195] Within months, Gamesa announced plans to establish a plant in Scotland.



Providing finance

Innovators need access to finance at key points in the innovation process. This can be to fund scale-up, to purchase capital equipment, or for a variety of other activities in the process. This capital may take many forms—equity or debt—and can come from public or private sources. The best known finance challenge is the 'valley of death' between product development and commercialization.[196] However, critical gaps may exist throughout the process.

To evaluate how effectively the innovation ecosystem is financing innovators, it is necessary to consider the needs for finance most common to the chosen technology. The infrastructure for wind power can be very capital intensive, for example.[197] Biogas can be done at many scales—from village level to utility scale—and each has a very different finance profile, depending for example on feedstock type, storage, availability of gas grid infrastructure, and other factors.[198] Choosing to focus on bringing more research in country will require supporting higher-risk applied science efforts at research institutions or industrial labs.

There can be many reasons why innovators cannot access finance. A typical example is that of a new company formed around a new idea. They have no assets, besides perhaps a handful of patents, and no revenues to borrow against, so raising capital from banks is very difficult. Large projects in developing countries would benefit from access to international sources of finance, yet international investors are often reluctant to provide capital because of currency risks and other "country risks". There is a wide range of other choke points. For example, banks may be reluctant to loan to solar or wind farm developers because they do not know how to properly perform the due diligence on the project—even though the farm itself represents significant assets and potential revenue.[199] This is an issue of information as opposed to actual risk. Alternatively, capital may be available but it may be very expensive.

Illustrative questions:

- Can power generators find financing for sound projects in a timely way?
- Do lenders understand how to evaluate risk properly in low-carbon technologies?
- How expensive is capital and how could its cost be reduced without introducing unreasonable risk to investors?

Some countries have already begun to provide finance at crucial stages. For example, the East of England Development Agency developed a "Low Carbon Innovation Fund" with £8 million from the European Regional Development Fund and at least £12 million from private co-investment.[200] The fund's goal is to invest in early venture capital stage small- and medium-size enterprises that provide low-carbon products, services, and operational changes.[201]

However, technology innovation funds only cover the earlier technology development phases. Other funding sources can help promote low-carbon solutions in the deployment stage, helping apply technological innovations. During deployment, financing needs change and other financing options become available, including venture capital, private equity, infrastructure financing institutions, and market mechanisms.[202] For example, the Urjankur Nidhi Trust Fund was established to "promote non-conventional energy projects" in Maharashtra, India. Funded by a tax on electricity consumption, the fund financially supports, via equity, the development of b-based co-generation power projects and will continue to provide support in later phases, including project management and power distribution.

Establishing governance and the regulatory environment

Every innovation ecosystem is strongly shaped by the existing governance and regulatory environment. A weak or stagnant regulatory environment can unnecessarily complicate or delay an innovation process.

When evaluating the existing governance and regulatory environment, it is critical to consider how flexible and adaptable the rules are. As innovators seek out new solutions, they will raise unanticipated issues. Addressing any potential negative impacts of a new product or process is important for successful innovation. As a result, a flexible and adaptable regulatory environment is just as important as a clear and enforceable one. For example, a crucial issue in CCS is incorporating new information.[203] Models; risk assessments; measuring, monitoring, and verification plans; and other required elements of a project are continually updated with new information. Many regulations are not only flexible enough to incorporate these updates but also call for them explicitly.

Illustrative questions:

- How does the current regulatory regime hold back innovators?
- What rules outside the energy sector impact innovation in the sector? Are land use rules, business formation regulations, or tax laws hampering efforts to innovate?

The rules of the game create incentives for different courses of action. These incentives might be financial, such as tax rates or subsidies. They might shape the risk profile of different activities and so benefit one option over another. The innovation process and the ecosystem it happens within are both complex and it is difficult to understand all the ways in which rules incentivize different choices. Nevertheless, some understanding of how incentives are impacting the innovation process in the target technology is important to deciding what may need to change.

It is also important to consider the full breadth of the rules that impact the innovator. In the context of globalized value chains, import and export governance is important. For example, technical standards and certification requirements that differ from country to country create an often-overlooked barrier to integration in global value chains in solar PV and wind power.[204] Environmental and land use rules can also strongly shape these innovation processes. For example, the expansion of biofuel use has engendered calls for strict standards to ensure net GHG emissions are reduced and that their production does not cause significant, negative impacts on food supplies and biodiversity.[205] An analysis should consider the clarity, appropriateness, adaptability, and incentive implications of the regulatory environment for every aspect of the chosen focus technology.

Creating markets

It is particularly critical in the low-carbon power sector to consider how markets are created. The fundamental product—electricity—is a commodity that is crucial to the larger economy and is under tremendous price pressure. The end user—the factory or home using the electricity—cannot tell if the electricity comes from high-carbon or low-carbon sources. Electricity is a highly regulated market because the infrastructure required to deliver it lends itself to a natural monopoly. These factors mean that policymakers have an unusually strong role in creating the market for low-carbon power, particularly until low-carbon options are fully cost competitive with often-subsidized fossil fuel options.

Many tools exist for market creation, from public awareness campaigns to regulatory requirements to government procurement. These are discussed in step three. In the current step, it is important to survey how effectively the market for low-carbon power options is functioning.

Illustrative questions:

- Does a market currently exist?
- How high are the barriers to entry? Is there a robust level of competition?
- Is it clear what characteristics the market will value highly, such as low carbon content, low cost, high reliability, and so on?
- Are there explicit barriers to low-carbon power participating in the market?

This analysis will have some overlap with the governance and regulatory environment analysis. The lines between these two functions are not bright, and often a single tool, such as a renewable energy law, can improve both functions. However, market creation goes beyond considering how the rules of the game shape the market and delves into how customer demand is being influenced more broadly.

If the low-carbon power sector goal chosen in step one includes building an export potential, it is important to evaluate how the target country supports its low-carbon market. Countries and even sub-national regions often work together bilaterally or multi-laterally to support the growth of markets in order to create export opportunities. Several initiatives under the Clean Energy Ministerial take this approach.[206]

STEP 3: Policy Making—Design and Implementation

Step two of this framework 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 for policymaking in the low-carbon power sector's innovation ecosystem**.

Box 8 | Summary Design Policy Principles

- Focus on improving the rate of change in price and performance.
- Design policies that are context sensitive and locally appropriate.
- Take a functional approach rather than a tool-centric approach.
- Design integrated and interconnected policies.
- Design durable, incremental policies to achieve cumulative change.
- Design robust but flexible policies.
- Design with evaluation and learning in mind.

Policy Design Principles

Focus on improving the rate of change in price and performance

Policy interventions must be designed to reward declining prices or improving performance and not simply to further deployment. In order to achieve the economic development, energy, and environmental goals outlined earlier, it is important to explicitly accelerate the rate of improvement. For example, air pollution regulation such as the U.S. Clean Air Act can drive innovation by setting a declining level of acceptable emissions.[207]

Simply encouraging increased deployment does not automatically ensure that innovation will occur, particularly in a heavily regulated marketplace such as the power sector. Deployment incentives can favor incumbents and hamper competition in some cases, depending on how they are designed. Some price decreases may be achieved through, for example, economies of scale or by removing market barriers that increase transaction costs. However, the transformational improvements necessary to reach sustained price declines and performance increases in the low-carbon power sector require successful innovations, which in turn require a robust innovation ecosystem.

Design policies that are context-dependent and locally appropriate

The innovation ecosystem approach does not list the top five policies every country or region should adopt. In the innovation ecosystem approach, "Innovation is seen as a cumulative process that is path-dependent and context-dependent. This is why innovation policy needs to build upon insight in a specific context and why 'best-practice' cannot be transplanted from one innovation system to another."[208] While there are lessons and success stories that can provide high-level guidance, each nation or region requires its own tailored and calibrated approach that addresses specific systemic failures in a way that is locally appropriate.

Take a functional approach rather than a tool-centric approach

The innovation ecosystem approach puts increasing the effectiveness and efficiency of one or more innovation ecosystem functions at the center of policymaking. Consider how the policy tools will support one or more of the functions. For example, participating in an international cooperation agreement can expand the collaborative networks available to innovators and help create and shape markets for their solutions.

Design integrated and interconnected policies

Collaboration will be critical to improve every function at the regional, national, and international level.[209] According to the OECD, "implementing an integrated innovation policy requires concerted efforts at many levels in many different organizations, including interfaces with the business sector and society at large, which together constitute the governance structure of the national innovation system."[210]

It may not be politically feasible, of course, to create a very broad policy package that radically changes the innovation ecosystem. In the United States, for example, it has been very difficult to move a national, comprehensive low-carbon legislative package forward. However, the President can take many smaller regulatory actions to improve the overall health of the innovation ecosystem.[211] The state-level governments that want to pursue low-carbon power also invest in their regional innovation ecosystems.[212] Together these efforts can result in more efficiently linked policies and policy delivery systems, and can have a significant impact on how successful innovators can be.

Design durable, incremental policies to achieve cumulative change

Is there a point at which the policymaker can do so little that it is not worth acting? Is it perhaps the case that only making small changes to improve the ecosystem is wasted effort because other systemic failures will doom innovators regardless? Quite the opposite.

Many of the capabilities that make innovation in this sector possible are cumulative, so beginning to learn has innate benefits. Radical changes may be difficult to institute for many reasons, including blocking by incumbents and a difficulty in absorbing changes. However, smaller, incremental changes that build on each other toward a more robust ecosystem can be a successful strategy.[213] Significant results in a relatively short period of time can be achieved by the "ratcheting up" of policy requirements, and even when large policy change is deemed possible, "it is no less important to reflect on what smaller calibrations of policy might have the potential to lead to even more durable change."[214] Though, it is important that these changes are well communicated to innovators so that they do not add to policy uncertainty.

In addition, policy interventions must be designed with durability—triggering greater support over time—and sustained commitment in mind.[215] The opposite of durability is change that appears to be significant but is in fact a reversal of previous policy, as is often the case following the election of a new government. This sort of back and forth policy oscillation is particularly damaging to the innovation ecosystem, as documented in the U.S. wind industry.[216]

The same principles apply to policies to create new collaborative networks. The OECD states that "Successful networking rests on trust between partners and trust requires time. Policies to promote networks should therefore be implemented and evaluated in a medium-term perspective (minimum 3-5 years), which implies stable funding and institutional settings. Frequent changes in policy goals, competing or poorly coordinated initiatives, and unstable financing of programmes are even more detrimental to network-oriented policies than they are to technology and innovation policy in general."[217]

Design flexible policies that adapt to the unforeseen
Policies should also be designed to ensure they are effective in multiple future scenarios; in other words, making sure that a policy is flexible. For example, as the climate changes, natural resource endowments and environmental pressures will change and could impact the power sector. A policy that is heavily fixated on hydrological resources for low-carbon power generation and that neglects to account for the possibility of changing water levels due to climate change is likely to run into serious complications. This is just one aspect of uncertainty in this rapidly changing global sector. Designing policy that is flexible in the face of multiple futures is essential to managing this uncertainty.

Design with evaluation and learning in mind
Step four will turn to evaluating the impact of the implemented policy package. During the design process, it is important to consider how the impacts of the policy will be measured.

There are two approaches in policy design that can explicitly enable learning: small-scale policy experiments and voluntary instruments. Sometimes policy interventions are purposely designed to have small-scale impacts upon implementation, as a way to learn from trial and experimentation without being exposed to large-scale negative impacts. Policies that seek to experiment are ideal candidates for evaluation, learning, and subsequent adaptation to a broader context.

Voluntary policy instruments can also provide the opportunity to learn while potentially limiting negative impacts.[218] For example, on the long road toward promoting low-carbon power generation at national scales, where special interests abound and policy interventions carry significant political risk, more and more states and utilities are providing consumers with the ability to choose non-fossil-fuel energy options on electricity bills. Such interventions pave the way for learning about consumer behaviors and may set the stage for mandatory approaches later.

Tools at the Policymaker's Disposal
A comprehensive list and analysis of individual policy tools that can support the innovation ecosystem is beyond the scope of this paper, and there are too many to make an exhaustive list. The OECD, for example, has recently outlined policy tools to pursue a green growth strategy that is heavily dependent on innovation.[219] Table 4: Sample Tools by Ecosystem Function provides a brief listing of the tools that might improve the effectiveness of the innovation ecosystem.

From Policy Design to Policy Adoption
Sometimes it seems there is a singular focus on implementing the most economically efficient or environmentally sound policy.

Table 4 | Sample 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 participant's 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

While striving for the 'best' policy is important, in an innovation ecosystem approach the 'best' policy is the one that suits the local context and supports innovators most effectively. This means the policy that can actually be implemented and bring about change is the 'best' policy. However, the innovation ecosystem approach also holds that change is constant, so new opportunities for better interventions may emerge and should be seized. The innovation ecosystem is never 'finished' or complete.

In light of this, it is important to consider prioritization of individual policy tools. In the context of competing interests and finite resources, “Governments must give priority to measures that have the greatest leverage effect on innovation processes. […] A strategic approach makes it easier to generate long term commitments for funding, remove inconsistencies in the incentive system, and formulate and communicate the government’s vision.”[220] There may be some ordering that is necessary, as functions can be dependent on each other. For example, a government cannot necessarily focus on market creation if there is no functioning grid to deliver electricity to customers. This dependency has to be blended with political and financial factors to determine which policies should be prioritized.

A second important aspect is political feasibility. For example, carbon taxes and cap-and-trade mechanisms are designed to account for the environmental and public health externalities of fossil fuel consumption. However, the resulting price increases seem to be politically infeasible in the United States today.[221]

Policy timing is a third important factor to consider in the policy process. In the United States, for example, a window of opportunity for the passage of a comprehensive national climate bill opened with President Obama’s newly elected government. The time was ripe to adopt new low-carbon energy policies, despite the subsequent failure of federal climate legislation. Conversely, following the failure of climate legislation, the window of opportunity closed for new comprehensive low-carbon policies to be implemented, though many more focused federal and state policies are still being adopted. In this context, policy approaches that take political timing into account will be more likely to succeed.

Box 9 | The Feed-in Tariff: An example of effective policy

At least 87 countries, states, and provinces currently have a feed-in tariff (FiT) to create markets for renewable energy.[222] This is a diverse set of countries, including developed economies like Germany, Spain, and some U.S. states; large emerging economies like China and many Indian states; upper-middle-income countries like Thailand; lower-middle-income countries like Sri Lanka; and low-income countries like Tanzania. Seventy-five percent of global solar photovoltaic capacity and 45 percent of global wind capacity was supported by FiTs in 2008.[223]

FiTs fulfill the market creation function of the low-carbon power sector innovation ecosystem, and they support other functions, such as providing finance. They can be a component of a successful innovation ecosystem, but only if they are explicitly targeted at innovation. The FiT experience in many countries also highlights the need to take a systemic perspective and consider the interactions with other policy interventions, to ensure other functions of the innovation ecosystem are being met.

Essentially a FiT provides eligible producers of renewable electricity the right to connect their projects to the grid, and to receive a guaranteed, pre-defined rate for every kilowatt-hour of renewable energy fed into the grid over a long period of time, usually 15 to 20 years. Growing, stable markets created by FiTs lead to more interest by the private sector in a given technology, to increased manufacturing, and to more experience with installation and operation of projects and their integration into the energy system[224]

However, the success of a FiT is not guaranteed, nor will it automatically lead to innovation. If technology providers and project developers know that they can rely on a subsidized, guaranteed rate, there is less of an incentive to pursue further cost reduction. To avoid this, mechanisms need to exist to review and reduce the subsidy to reflect innovation in the sector. For example, the Philippines has set annual deployment targets; if they are dramatically exceeded or not achieved at all, a review process will reconsider the rates and adjust them accordingly for the next year.[225]

To create a stronger mechanism to encourage innovation, these regular reviews can be complemented by regular, pre-announced reductions of the tariff (degression). In Germany, independent of any additional adjustments, FiT rates fall by a given percentage annually.[226] Increasingly, degression is also used in developing countries; for instance, Malaysia and the Philippines will both use preannounced degression schedules in their solar PV FiTs that are bound to go into effect in 2011.[227]

Finally, it should be noted that FiTs in isolation would not lead to additional deployment, let alone innovation. Rather, broader enabling conditions are needed in power sector regulations, investment and financing conditions, suitable electric grid infrastructure, and technical capacity.[228]

For example, the Thai FiT was only successful because it included interconnection rules; that is, because it also addressed an aspect of the governance and regulatory environment function. These rules provided a predictable and easy-to-navigate way for small independent power producers to ensure their electricity would be bought by the utility.[229] Similarly, policy interventions might be needed to make sure finance is provided to those who want to manufacture, install, or operate renewable energy technologies. In Thailand the government loaned 4 billion baht (US$133 million) to 13 commercial banks at 0.5 percent interest under the condition that the capital was used to provide loans of up to 50 million baht (US$1.6 million) to small power projects at preferential 4 percent interest rates.[230]

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

At this point a target technology has been chosen based on the 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. This is hardly the end of what will be a long road. Innovation ecosystems take time to mature and bear fruit.[231]

Evaluating the policies to consider how well they have attained their goals, and then adapting them if necessary, is a critical next step in the process of building a robust innovation ecosystem. According to the OECD, "One of the key implications of a systemic approach to innovation policy is that governments need to learn more about intended and unintended effects of interacting policies. […] Policy learning through cycles of experimentation, evaluation and adaptation of objectives and instruments is key to long term success."[232]

Why Evaluate?

It is best practice to evaluate whether a policy has achieved its intended purpose and whether it has had unintended consequences or benefits. Policy evaluation offers the opportunity to consider how to become more effective in the future.[233] In a sector as new as low-carbon power, there is also intense interest from other governments to learn from evaluation what policies work under what circumstances.

When taking the innovation ecosystem approach, the constant evolution of the system is also a key reason to evaluate the impacts of a policy. While policies were ideally designed to be flexible and accommodate the unforeseen, systemic change can blunt or amplify their impact. As a policy—or even just the expectation of a policy—comes into effect, innovators begin to change their strategies in order to adapt to the changing ecosystem. The global low-carbon power sector will also continue to mature over time. The technologies will change and evolve. Other governments put their own policy changes in place in response to changes in this country. All of this results in significant and potentially rapid change in the innovation ecosystem. New systemic failures can arise and old failures fester. The landscape and functional analyses in steps one and two were accurate only for a particular moment in time. As time passes, a revised analysis is needed and policy changes may be necessary to address the new challenges. This means there are two dimensions for policy evaluation:

- The first is understanding how effectively or ineffectively the policy choices made in step three impacted the innovation ecosystem functions.
- The second is understanding how the global low-carbon power sector landscape has changed and what this implies

for how effectively the functions are being delivered today.

Evaluate What?

There is significant debate on how to effectively measure innovation activities and successes.[234] One approach is to measure inputs, such as private sector investment in research and development. This has many drawbacks, such as not being sure whether the inputs are actually increasing the odds of success for innovation processes. The OECD regularly collects a great deal of data about inputs to the innovation ecosystem like R&D budgets and how they are spent; academics mine this data but bemoan its limitations.

There are also efforts to track outputs, such as patents and academic articles. For example, a 2009 report analyzed patents and patent citations for low-carbon power technologies partly to evaluate diffusion and technology transfer rates.[235] This sort of analysis can usefully identify trends and chokepoints, but is likely only a first step. The key challenge with this approach is that the outputs only imperfectly represent the number of successful innovation processes. An innovation may never be patented and a patented idea may never come into commercial use. Other output measures have similar challenges in truly capturing successful innovations, particularly in processes as opposed to products.

The European Community Innovation Surveys are very detailed in the data they collect and the number of companies they reach. They offer a model for monitoring innovation activities that other countries might find useful. However, a quantitative measure like surveys may require multiple applications in order to identify changes in trends. This is challenging in many developing countries and in a rapidly maturing sector that is undergoing so much structural change.

None of these approaches, however, satisfyingly attributes the cause of any broad changes in the ecosystem. It can be difficult to determine for example that a particular policy explicitly increased the competitiveness of an economy or encouraged innovators to take more risks.[236]

In part to address this problem of attribution and in part because accelerated innovation alone is not the goal—it is the strategy that makes it possible to reach the long-term goals—this paper adopts a staged evaluation approach:

- First, evaluate the impact of the policies implemented in step three on the innovation ecosystem functions.
- Then turn to whether innovation is accelerating through improved cost and performance metrics.
- Finally turn to evaluating progress on the goals set in step one.

Approaches to Evaluation and Learning

It is best practice to look to external and independent evaluators in order to ensure an effective analysis of the success of a policy.[237] The intention is to learn in order to tune the policy intervention to be more effective. An external evaluator can be more objective and improve transparency and accountability, which are key features of good governance and critical to effective stakeholder engagement.

While it is critical to avoid regulatory capture and coddling of incumbents that in turn chokes out true innovators, the users of the innovation ecosystem remain a critical source of data on where new systemic failures are arising. Just as step two looked to stakeholders to help identify systemic failures, the current evaluation should similarly seek their input. The challenge is that the goal of improved performance or lower cost may run counter to incumbents who push to ensure the ecosystem favors their solutions, even if they are not the best available. Seek a careful balance between competition and support for innovators.

Determine whether the innovation functions are being delivered more effectively and efficiently

Steps two and three sought to analyze innovation ecosystem functions, and craft and implement policy solutions to strengthen function delivery. Is this happening or not? For example, if providing finance was identified as a weak function, and the subsequent policy solution was to create a new ‘green bank’, evaluate whether the green bank is indeed facilitating access to finance. Criteria may include the number of small and medium enterprises that have applied for capital, the number that have been approved, whether the time that it takes to receive a loan has decreased, whether the cost of capital has decreased, the number of loan guarantees that have been issued, etc. The criteria should be specific to the policy instrument used and the ecosystem functions it was intended to improve. In step three, as the policies were crafted, measurement mechanisms should have been included in the design where possible.

Measure the rate of change in cost and performance
Having evaluated the impact that policies have had on the effectiveness and efficiency of innovation ecosystem functions, the next question is whether improvements in innovation function delivery are leading to accelerated innovation, i.e., to decreases in cost and increases in performance. Criteria to evaluate may include the cost of low-carbon electricity per kilowatt-hour, the duration of power outages, the number of low-carbon power generation safety accidents, the improvement in technology quality standards, etc.

Evaluate progress toward the vision of long-term sustainable development
Having evaluated the delivery of the innovation ecosystem functions and whether or not policies are actually translating into innovation in the low-carbon power sector, the next level of evaluation is whether or not innovation in the low-carbon power sector is contributing toward achieving long term economic development, energy, and environmental goals.

There are a great many efforts to provide measures for sustainable development and these can be adapted from the literature to best meet the policymaker's context. For example, Table 5 quotes the OECD's green growth indicators.

Evaluate the functions and landscape again
Having evaluated the impact of the policy package on the innovation ecosystem functions, it is important to understand how the ecosystem is changing more broadly, by repeating steps one and step two. This analysis may be smaller in scale than the original analysis and should be simpler since it has been done once before. However, it is critical to track how the global innovation ecosystem has changed, how the national or

Table 5 | Overview of Proposed Indicator Groups and Topics Covered, from OECD's *Toward Green Growth*[238]

Issue	Indicators
The environmental and resource productivity of the economy	• Carbon and energy productivity • Resource productivity: materials, nutrients, water • Multi-factor productivity
The natural asset base	• Renewable stocks: water, forest, fish resources • Non-renewable stocks: mineral resources • Biodiversity and ecosystems
The environmental dimension of quality of life	• Environmental health and risks • Environmental services and amenities
Economic opportunities and policy responses	• Technology and innovation • Environmental goods and services • International financial flows • Prices and transfers • Skills and training • Regulations and management approaches
Socio-economic context and characteristics of growth	• Economic growth and structure • Productivity and trade • Labour markets, education, and income • Socio-demographic patterns

regional ecosystem has changed, how the technologies and the opportunities they present have shifted, and so on.

This iteration should not imply that the first analyses were failures or wasted effort. Adopting a systemic approach means accurately reflecting the complexity of the real world, including how the sector is rapidly moving and changing. This pace of change is part of the reason there is a chance for new participants to seize opportunities. No policy environment is ever 'complete'. Individual policies may come to an end when they are no longer effective or needed, but the larger system is always changing, and to ensure that policy does not become the cause of new systemic failures, repeated analyses are necessary.

Update policy where necessary
Having evaluated and learned, it is critical to complete the cycle by adapting. This is accomplished by repeating step three in order to update, cancel, change, or otherwise refine the policy package to ensure it is successfully improving the ecosystem functions. This step can be built into the original policy design by setting an administrative process. Many regulations limiting pollutants include a similar process to reset acceptable levels based on new information. Adapting to a changing context and taking advantage of learning is central to ensuring the ecosystem continues to foster innovation.

CONCLUSION

This paper has tried to articulate why policymakers would put innovation at the center of a green growth strategy and the web of benefits that the literature, decades of evidence, and low-carbon trends point to. It has described the innovation ecosystem approach, which allows policymakers to more effectively intervene to support and unleash innovators. Finally, it has articulated a step-by-step process for pursuing an innovation-centric strategy. This iterative process is never complete but addresses the need to be constantly adapting to the rapidly changing landscape.

There is a short window of opportunity to act on low-carbon power. The ever-increasing annual measures of CO_2 in the atmosphere and the mounting evidence of ongoing fundamental climate changes suggest the window for transformation is very small.[239] There is little debate that the emissions trends must reverse; the curve must bend within the decade and likely sooner.

For those innovators, countries, and regions that want to secure their place in the new sector, the timeframe is equally short. The existing commitments to reduce emissions create a significant market, and every indication is that this sector will continue to grow. As it rapidly matures, the opportunities to enter and effectively compete will disappear. As we have seen, the cumulative nature of innovation means that the barriers to entry will only increase. Now is the moment to bet on this sector's long-run potential.

The scale of the unknown matches this urgency. While the global community has pursued economic development as an explicit strategy for more than fifty years, and innovation policy since the 1980s, there are many firsts in this effort. This is the first time emerging economies are poised to play an important role in the frontier of the technologies. This is the first time a global sector has been created in such a rush.

This level of uncertainty suggests that further research is needed to identify which principles and approaches lead to success and which fail. This framework in particular would benefit from more dialogue with policymakers and additional case studies or joint analysis with decisionmakers in country. It will also be critical to share information widely whenever possible. Just as it is critical for product and process innovators to have access to collaborative networks and new knowledge, policy innovators would benefit from fostering a community of practice and providing it with an evidence base.

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. As discussed above, innovation has already dramatically reduced the cost and improved the performance of the technologies we need to rely on. But there is clearly more to do. 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 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.

APPENDIX A: Evolutionary Economics versus Neoclassical Economics

Jorge Niosi summarized the main differences between evolutionary economics and neoclassical economics in his 2010 book on innovation systems, and Table 6: Evolutionary Economics Compared to Neoclassical Economics largely quotes his work.[240] The innovation system model evolved alongside evolutionary economics, particularly through Richard Nelson's work. As a result, understanding the differences between neoclassical economics and evolutionary economics can shed light on why the innovation system approach calls on the policymaker to consider more than discreet market failures in the innovation process.

Table 6 | Evolutionary Economics Compared to Neoclassical Economics

Issue	Complexity and Evolutionary Economics	Traditional Economics
Micro-Foundation	Bounded rational agents learn and adapt their behavior; knowledge comes in different forms (e.g., tacit, codified) and is different from information; agents do not have complete information	Perfect rational agents make no errors, do not learn and have complete (or almost-complete) information
Dynamics	Open, non-linear systems usually out of equilibrium	Closed systems, static, linear systems in equilibrium
Links Among Agents	Many different types of links (technological, financial, personal, regulatory), including co-operative and competitive	Links among agents occur through market mechanisms
Relation Between Micro- and Macroeconomics	No division between micro-and macroeconomics; macro-patterns emerge from micro-level behavior and links	Micro- and macroeconomics are different disciplines
Evolution	Evolutionary processes of variation, selection, and retention at many levels (technologies, firms, industries) provide novelty	No explicit mechanism processes, technologies and product emerge (no mechanism for novelty)
Theory Development	Basically inductive: systems are discovered, as in natural science	Basically deductive
Policy	Specific to national, regional and sectoral systems and their specific context	One-fits-all policy prescriptions
Models	Complexity models, game theory, statistics, scientometrics	Calculus, algebra
Economic Growth	Occurs through creation of new products, and sectors	Occurs through addition of capital and labour and increase of productivity
Technology	Studied as endogenous to economic system and key determinant of growth	Exogenous to the economic system
Time	Time scales are key (i.e., for learning, institutional change)	Time is usually out of the models

APPENDIX B: The Technological Regime of the Low-Carbon Power Sector

The analysis summarized in Table 7: Analysis of the Low-Carbon Power Sector Technological Regime is adapted from Breschi and Malerba's conception of the attributes and dimensions that define a technological regime.[241] The table applies the attributes they identify as critical to the low-carbon power sector as it functions today, and forms the foundation for the analysis of how the technological regime shapes the innovation process and industry broadly in Innovating in the Low-Carbon Power Sector above. Since the low-carbon power sector is still a very broad group of heterogeneous technologies, this analysis could be done on a much narrower set of technologies, or even a segment of a value chain, as part of the technological review in STEP 1: Global Value Chain Assessment and Positioning.

It is understood in the academic literature that sectors mature over time and, as a result, the technological regime will change and shift.[242] Thus, some of this analysis is applicable today but will become inaccurate as the sector grows and matures. As a result, it will be useful to re-evaluate this analysis as a part of STEP 4: Policy Monitoring, Evaluation, Learning, and Adaptation.

Table 7 | Analysis of the Low-Carbon Power Sector Technological Regime

Attribute	Dimension	Definition	Applied to the Low Carbon Power Sector
Opportunity		The chance of innovating for any amount of resources invested in searching for solutions.	
	Level	High level of opportunity – a high chance of innovating based on an investment in searching. Low level of opportunity – a low chance of innovating based on an investment in searching, typically found in very mature industries.	Low-carbon power technologies have not yet settled into dominant designs for the most part, apart perhaps from wind turbines. The National Renewable Energy Lab tracks 12 types of solar photovoltaic applications.[243] The best ways to produce biofuels and the optimal ways to operate concentrating solar power plants all remain to be settled. There is a high level of opportunity.
	Pervasiveness	High pervasiveness - new knowledge applies to several markets or products. Low pervasiveness - new knowledge applies to only a few products.	Low-carbon power technologies are highly heterogeneous[244] and this means there is low pervasiveness across the sector. For example new knowledge related to a solar technology is not highly applicable to other technologies, or even across solar applications. Developing new battery materials may be useful in many products, but new software to turn heliostat mirrors to follow the sun is useful in fewer applications.
	Variety	High degree of variety – there is a large range of possible solutions, approaches, or activities, typically the case when a sector is young. Low degree of variety – dominance of one design or approach, typically after the sector has consolidated. The search then shifts to improving performance of the dominant approach rather than developing radically new approaches.	There is a high degree of variety in the low-carbon power sector today. For each technology there are myriad choices and many methods of production, operations, and maintenance.

Sources	The origin of innovations. This may include, for example, basic science, advances in instrumentation, or learning from suppliers and customers.	Different aspects of the low-carbon power sector rely on different sources for innovation. Some of the technology is deeply rooted in science, while issues like siting wind turbines and achieving high capacity factors relies on excellent instrumentation and learning.
Appropriability	The possibilities of reaping profits from the innovation processes.	
Level	Low appropriability - widespread knowledge spillovers and imitation. High appropriability - larger incentive to the innovator, less knowledge sharing.	There is high appropriability in the utility-scale low-carbon power sector from a knowledge perspective. However, reaping profits from an innovation in the low-carbon power sector is complicated by the need to integrate with the mature, highly regulated electricity sector, where they face significant price pressure. The possibilities of making a profit are high today only in those markets where there is a constraint on carbon emissions, support for low-carbon options, or costs for high-carbon options.
Means	The ways used to ensure appropriability. These may include patents, continuous innovation, trade secrets, and the control of complementary assets. The effectiveness of these means shapes the nature of the knowledge spillovers.	Patents are used and defended by equipment manufacturers[245] in this sector. Trade secrets and non-disclosure agreements are also widely used. Companies are very cautious about who has access to information on their processes, designs, and the supporting knowledge bases. The highly tacit nature of the knowledge (see below) makes the trade secret approach quite effective, but also increases the value of highly skilled, well-networked individuals.
Cumulativeness	The degree of correlation between innovations; how dependent or connected the next innovation is to the prior innovation. There are three levels of cumulativeness.	
Firm	Firm-level cumulativeness - continuity of innovative activities strongly depends on the competencies of specific firms.	In this sector, innovations are quite cumulative at the firm level. In part this is driven by the high capital costs and long design cycles of innovations. In part this comes from the highly tacit nature of the knowledge.
Sector	Sector-level cumulativeness –innovations building on one another across the entire industry, particularly in cases of low appropriability where the knowledge base diffuses widely.	There is some sector-level cumulativeness, but for the reasons given above, it is relatively weak compared to firm-level cumulativeness.
Local	Local cumulativeness – Highly localized knowledge spillovers leading to concentrated innovation activities in a specific geographical area.	This sector does not display the sort of geographic consolidation that is found in biotechnology or information technology, despite the high level of tacit knowledge. There is some

		regional consolidation, where the next set of innovations is built on the prior regionally specific innovations. These are perhaps driven more by access to large markets with regionally specific needs.
Knowledge Base	The properties of the knowledge that innovation is based on.	
Generic / Specific	Generic knowledge – widely applicable Specific knowledge – applicable only to a well-defined domain.	The knowledge in this sector is highly specific, even to the individual technologies within the sector.
Codified / Tacit	Codified knowledge - easily reproduced in writing, for example in scientific articles, blueprints. Tacit knowledge - tied to specific people with long experience.	Much of the knowledge is tacit. While the mechanical aspects of individual technologies may be codified in blue prints and scientific articles, how to effectively manufacture, site, and operate the equipment is highly dependent on tacit knowledge. Similarly, the knowledge required to integrate variable power sources like wind and solar into the larger grid is deeply dependant on an understanding of the specific grid, its fuel sources, its loads, and its technical capabilities.
Simple / Complex	Simple knowledge – can be understood and applied independent from other disciplines Complex knowledge - deeply integrated with other disciplines or a variety of competencies.	The knowledge in this sector is very complex, requiring integrated understandings across many competencies.
Independent / System	Independent knowledge - easy to identify and isolate System knowledge - embedded in a larger system and difficult to split out.	The knowledge is not easily isolated but is embedded in the context of the location, technology, resource, and electrical system.

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[44] Verspagen, "Innovation and Economic Growth," 492.

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[73] The graphic slightly understates the story; the difference in number of turbines needed is so large that it was necessary to round up to make the comparison visible at all. Each turbine in the graphic represents approximately 1 million turbines. The 50% reduction goal could be met by 1.25 million 1.6 MW turbines and 200,000 10 MW turbines. In addition, these calculations focus on horizontal-rotor, onshore wind turbines and treat the 2,000 GW target as “nameplate” capacity. The cost calculations use estimates of the levelized (or lifecycle) cost of energy (or electricity) and compute the cost of producing 5,200 TWh of wind energy, which is stipulated in the IEA Blue Scenario Wind Goal.
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[76] Slappendel, “Perspectives on Innovation in Organization,” 107.

[77] Ibid.; Fagerberg, “Innovation: A Guide to the Literature”; Johannessen, “A systemic approach to innovation: the interactive innovation model.”

[78] Slappendel, “Perspectives on Innovation in Organization.”

[79] Gallagher, Holdren, and Sagar, “Energy Technology Innovation,” 195.

[80] There is no consensus among academics on the criteria for 'successful innovations', however adoption is a common theme. (Johannessen, “A systemic approach to innovation: the interactive innovation model.”) Given the urgency of the challenges that innovation in the low-carbon power sector seeks to address, this paper argues that an innovation must be adopted by enough actors to influence the marketplace. That could be a single manufacturer or all of the transmission operators in a region. The important measure is impact on cost or performance of the technology in the sector.

[81] Fagerberg, “Innovation: A Guide to the Literature.”

[82] General Electric Company, “Combined Cycle - FlexEfficiency Power Plant Technology”, n.d., http://www.ge-energy.com/solutions/combined_cycle_power_plants.jsp.

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[85] Schumpeter, *The Theory of Economic Development*; Johannessen, Olsen, and Lumpkin, “Innovation as newness: what is new, how new and new to whom?”; Slappendel, “Perspectives on Innovation in Organization.”

[86] Pavitt, “Innovation Processes”; Kline and Rosenberg, “An Overview of Innovation.”

[87] Kline and Rosenberg, “An Overview of Innovation”; Mowery and Rosenberg, “The influence of market demand

upon innovation: a critical review of some recent empirical studies."

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

[89] Fagerberg, "Innovation: A Guide to the Literature," 5.

[90] Schumpeter, *The Theory of Economic Development*, 85; Nelson and Winter, *An Evolutionary Theory of Economic Change*, 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*.

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[93] This model originates in a widely cited 2004 article by Michael Grubb (Grubb, "Technology Innovation and Climate Change Policy: an overview of issues and options.") In the original article, there is extensive discussion of the limitations of this simplified model. But the model serves the author's purpose of illustrating the types of financing needed at different phases of a generalized innovation process and introducing the climate mitigation community of practice to the technology push / market pull debate ongoing in the innovation literature. However, beginning as early as the late 1970's, researchers on innovation were refuting the simple linear models of innovation that many economists had been relying on since the 1930's. Kline and Rosenberg's seminal article in 1986 (Kline and Rosenberg, "An Overview of Innovation.") coincided with a shift toward studying innovation systems, rather than innovative companies, and was a turning point in how innovation processes were conceptualized.

[94] This figure is adapted from *The Great Green Technological Transformation*, 136., which itself draws from forthcoming background papers by A. Grubler and K. Sims Gallagher.

[95] Edquist, "Systems of Innovation: Perspectives and Challenges," 188.

[96] Nelson, *National Innovation Systems: A Comparative Analysis*; Bengt-Åke Lundvall, *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning* (London: Pinter Publishers, 1992).

[97] Edquist, "Systems of Innovation: Perspectives and Challenges."

[98] Ibid.

[99] Niosi, *Building National and Regional Innovation Systems: Institutions for Economic Development*, 34.

[100] Niosi, *Building National and Regional Innovation Systems: Institutions for Economic Development*; Nelson, *National Innovation Systems: A Comparative Analysis*.

[101] *Dynamising National Innovation Systems*.

[102] Ibid.

[103] Edquist, "Systems of Innovation: Perspectives and Challenges."

[104] In 2009, India's Ministry of New and Renewable Energy announced the Jawaharlal Nehru National Solar Mission, a mission to install 20GW of solar-powered electricity generation capacity by 2022. The long-term objective of the National Solar Mission is to establish India as a global leader in solar energy. The immediate aim of the Mission is to set up an enabling environment for solar technology penetration in the country. It is envisioned that as a result of the Mission the price of solar electricity will attain grid parity by 2022. (Indian Ministry of New and Renewable Energy, "Government announces Jawaharlal Nehru National Solar Mission", n.d., http://mnre.gov.in/pdf/Minister-announced-JNNSM.pdf.)

[105] Niosi, *Building National and Regional Innovation Systems: Institutions for Economic Development*.

[106] Ibid.; "Jawaharlal Nehru National Solar Mission - Towards Building SOLAR INDIA."

[107] Opportunities to share non-competitive information should not be underestimated or overlooked. Policymakers can benefit from sharing best practices and lessons learned in their efforts to support this sector. Transmission operators are typically not competing with each other and can benefit from sharing both technical and procedural best practices for managing low-carbon power on the grid. Information about resource assessments, policy environments, and other services can improve competition in the sector and can lower barriers to entry for new innovators. While there will always be proprietary information that companies or governments want to hold close for competitive reasons, there is a great deal of non-competitive information that the innovation ecosystem should support sharing in order to support innovators.

[108] Nelson, *National Innovation Systems: A Comparative Analysis*, 16.

[109] Chris Freeman, "The 'National System of Innovation' in historical perspective," *Cambridge Journal of Economics* 19, no. 1 (February 1, 1995): 5 -24, http://cje.oxfordjournals.org/content/19/1/5.abstract.

[110] *Dynamising National Innovation Systems*.

[111] Edquist, "Systems of Innovation: Perspectives and Challenges."

[112] Fox-Penner, *Smart Power: Climate Change, The Smart Grid, and the Future of Electric Utilities*.

[113] Richard Nelson as early as his 1992 book with Sidney Winter on evolutionary economics discussed the technological regimes that firms operate within. Though, Nelson and Winter were not the first or only writers to discuss technological systems. Stefano Breschi and Franco Malerba significantly developed the idea in their 1997 article, "Sectoral Innovation Systems: Technological Regimes, Schumpeterian Dynamics, and Spatial Boundaries" and in their later work.

[114] Franco Malerba, "Sectoral Systems: How and Why Innovation Differs Across Sectors," in *The Oxford Handbook of Innovation* (Oxford: Oxford University Press, 2006), 380-406.

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[117] Gallagher, Holdren, and Sagar, "Energy Technology Innovation," 202.

[118] Ibid.

[119] Hiroki Hondo, "Life cycle GHG emission analysis of power generation systems: Japanese case," *Energy* 30, no. 11-12 (August): 2042-2056, http://www.sciencedirect.com/science/article/pii/S0360544204003652.

[120] Tom Kerr, *CCS Roadmap*, 24.

[121] Charles Weiss and William Bonvillian, *Structuring an Energy Technology Revolution*.

[122] Tawney, Greenspan Bell, and Ziegler, *High Wire Act*.

[123] Matthew L. Wald and John M. Broder, "Utility Shelves Ambitious Plan to Limit Carbon," *The New York Times*, July 13, 2011, sec. Business Day / Energy & Environment, http://www.nytimes.com/2011/07/14/business/energy-environment/utility-shelves-plan-to-capture-carbon-dioxide.html.

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[125] Ove Grandstrand, "Innovation and Intellectual Property Rights," in *The Oxford Handbook of Innovation* (Oxford: Oxford University Press, 2006), 266-290.

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[131] Eric Lane, "In Wind Patent War, Mitsubishi Fires Back at GE with Antitrust and Patent Infringement Suits," *Green Patent Blog*, June 7, 2010, http://www.greenpatentblog.com/2010/06/07/in-wind-patent-war-mitsubishi-fires-back-at-ge-with-antitrust-and-patent-infringement-suits/.

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[135] Between 2008 and 2010, only two companies (Acciona and Nordex) fell off the list of the top 10 wind turbine manufacturers (measured in share of new installed capacity) and two new Chinese entrants (Dongfang and United Power) joined the list. At the same time, the positioning within the group changed frequently. For instance, Chinese turbine manufacturer Sinovel ranked 7th in 2008, 3rd in 2009 and 2nd in 2010. Likewise, GE slipped from 2nd to 3rd place in 2010 and Siemens from 6th to 9th in 2009. The most notable trend is the emergence of Chinese manufacturers, which is related to China becoming the world's largest wind power market. There were three Chinese companies among the global top 15 in 2008, five Chinese companies in 2009 and seven Chinese companies in 2010. BTM Consult, *International Wind Energy Development: World Market Update 2008* (Ringkøbing: BTM Consult, March 2009), http://www.btm.dk/reports/previous+reports/world+market+update+2008/?s=55; BTM Consult, *International Wind Energy Development: World Market Update 2009* (Ringkøbing: BTM Consult, March 2010), http://www.btm.dk/reports/previous+reports/world+market+update+2009/?s=58; BTM Consult, *International Wind Energy Development: World Market Update 2010* (Ringkøbing: BTM Consult, March 2011). Similar developments, with an even faster rise of Chinese manufacturers, have been observed in the solar sector. See

for instance Keith Bradsher, “China Racing Ahead of U.S. in the Drive to Go Solar,” *The New York Times*, August 25, 2009, sec. Business / Energy & Environment, http://www.nytimes.com/2009/08/25/business/energy-environment/25solar.html?ref=solarenergy.

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[137] Andy Paliszewski, March 3, 2011.

[138] Kirkegaard, Hanemann, and L. Weischer, *It should be a breeze*.

[139] *Dynamising National Innovation Systems*, 55.

[140] *Dynamising National Innovation Systems*; Niosi, *Building National and Regional Innovation Systems: Institutions for Economic Development*.

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