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Harnessing Energy-Technology Innovation in Developing Countries to Achieve Sustainable Prosperity

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Background Paper

World Economic and Social Survey 2011

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January 10, 2011

I. Executive Summary

How to harness innovation to achieve sustainable prosperity? Developing and industrialized countries alike are trying to answer this question, and many countries are already experimenting with policies and programs in their quest to actualize a green economy. This paper reviews the current understanding in the scholarly literature about the key processes and functions of innovation systems. Knowledge about energy-technology innovation systems is explored in further detail since energy use is at the heart of many environment and development challenges. Two contrasting case studies related to solar PV are presented: (1) deployment of off-grid solar PV technology in Bangladesh, and (2) development of a solar PV manufacturing industry in China. Policy implications and lessons for other countries are provided for each case, and then broader policy recommendations are offered in the concluding section.

II. Introduction: The Innovation Challenge in Developing Countries

Scope of the Challenge

Achieving a green economy and sustainable prosperity will require innovation, including: new technologies for the generation and delivery of energy services like electricity, transportation, and industrial production; new technologies for agricultural production; and new methods to ensure the integrity of ecosystems. These innovations will require (i) research and development to invent new technologies; (ii) new methods of reducing the cost and improving the performance of current technologies; and (iii) crafting incentives that enable these technologies to diffuse across international borders. In short, the entire *system* for innovation (discussed in more detail in Section 3) must be engaged in order to achieve sustainable prosperity. We use the term ‘sustainable prosperity’ rather than ‘development’ because it connotes a healthy, vigorously growing, and successful society, not one perpetually striving to develop. We recognize, of course, that achievement of true sustainability – where there is no diminution of ecological conditions or processes – will be difficult.

Effectively harnessing an innovation system requires engagement of the private and public sectors. The private sector combines entrepreneurial drive with research and development to create markets and diffuse new technologies while the public sector can create and implement policies that incentivize technology diffusion and provide resources that support research, development, and demonstration (RD&D). These various actors and institutions must engage in an interdependent, iterative, and intricate dance in order to achieve effective development and deployment of new technologies that will enable sustainable prosperity. Because of this complexity, simply setting a policy goal of spurring or accelerating innovation is no guarantee of success.

The process of innovation is difficult for *all* countries, but the unique challenges faced by many developing countries compound the challenge. Because innovation systems operate in a context-dependent manner, the diverse capacities and resource endowments of individual developing countries bear on the potential for results from innovation systems. In particular, many developing countries exhibit weaker capacities in some or all dimensions for effective innovation. Effective research and development, for example, involves the engagement of research universities, which in turn rely upon a solid primary and secondary education system for the generation of human capital that is an essential input into the innovation process (Arocena and Sutz, 2005). Effective market formation for new or cleaner technologies relies on a robust regulatory, legal and institutional framework. Furthermore, social institutions must participate in the innovation system (Niosi 2002). Identifiable gaps in developing country innovation systems exist in all of the institutions for change, and in particular in frameworks for knowledge development (Gu 1999).

National innovation systems do not operate in an autarkic vacuum: international technology cooperation, technology spillovers, knowledge development and learning, and technologies themselves can move across national boundaries and respond to international bilateral, multilateral and international agreements. Technology transfer and the possibility of “leapfrogging” stages of technological development also form part of the innovation equation for developing countries, but these process vary widely depending on the sector and are rarely automatic (Brezis et al. 1993, Goldemberg 1998, Gallagher 2006).

Developing countries are highly heterogeneous; not only are the institutional contexts of many countries highly variable, but the technological and infrastructural needs of many countries are profoundly different. Because effective innovation systems are dependent upon the context in which they are situated, there is no “one-size fits all” or “silver-bullet” strategy for mobilizing effective innovation systems in developing countries for sustainable development (Arocena and Sutz, 2005; Intarakumnerd et al. 2002).

Main Aims and Structure of Paper

Because of the importance of effective innovation systems for sustainable development and the creation of a green economy, the different circumstances that affect the successful development of effective innovation systems in developing countries merit attention. Understanding these processes is complicated because the processes that control innovation are complex and the factors that influence these processes vary across developing countries. This paper aims to unpack these factors in order to suggest how we might address these unique and complex challenges.

The paper begins with a thorough characterization of innovation systems, with particular, though not exclusive, attention to energy-technology innovation systems. In the next section, we present a typological framework of ways to categorize developing country innovation systems and the factors influencing the innovation challenge in different developing countries. In order to illustrate these systems and challenges, we present short comparative case studies of solar-photovoltaic technology innovation and diffusion in two vastly different developing country contexts: China and Bangladesh. Finally, we conclude with policy recommendations for meeting the innovation challenge in developing countries and achieving sustainable prosperity.

III. Innovation Systems

A Systemic Perspective on Innovation

Innovation is an integral component of the development process related to the exploitation of natural resources, be they energy resources, fisheries, land for agricultural production, or the generation of new industries and economic production methods. Because of its role in driving all engines of an economy, innovation is essential to the achievement of sustainable prosperity, and its effectiveness is a key to unlocking the pathways to a green economy.

Unlike natural resources, innovation is a human-generated resource. Also unlike natural resources, innovation cannot be understood as a purely quantitative variable; it is a process of interrelated and interdependent stages that influence each other in non-linear ways (Mowery and Rosenberg 1979; Landau and Rosenberg 1986; Freeman 1994). The stages of the innovation process include research, development, demonstration, market formation, and finally the culminating pervasive diffusion of technologies. These stages—and the policies, actors and institutions which influence them—can be understood as part of an *innovation system*, shown in the chain-link model in Figure 1, through which new technologies and organizational processes enter into societal and economic usage (Nelson and Winter 1982; Freeman 1988; Lundvall 1992; Brooks, 1995; Grubler, A., et al., 2011).

Within this innovation system model, feedbacks exist between stages, which often overlap with one another in temporal space; in some cases stages may be skipped, or are not applicable to a given technology or process (Grubler, 1998). Often, the greater the interaction among stages, the more efficient the innovation process.

When analyzing an innovation system, different, interacting forces can be identified. Different stages of innovation interact through both “supply push” and “demand pull” forces, both of which encourage the generation of new knowledge (see Halsnaes et al. 2007 for a review of these dynamics) These dynamics must be understood within the institutional context (represented by the blue ovals in Figure 1) in which the innovation process is at work (Nelson, 1993; Geels, 2004). For the consideration of this paper, the institutional context, as well as specific national, geographical or technological factors are all considered variables that influence the innovation processes. Because these factors vary across developing countries, they must play a central role in our consideration of innovation systems. These factors are discussed in the next section.

The innovation system can be further categorized into stages of maturity over time. While the internal dynamics of the innovation system are characterized by internal feedbacks and non-linearities, a national system of innovation is developed through an iterative process which takes time, typically decades (Nelson 1993).

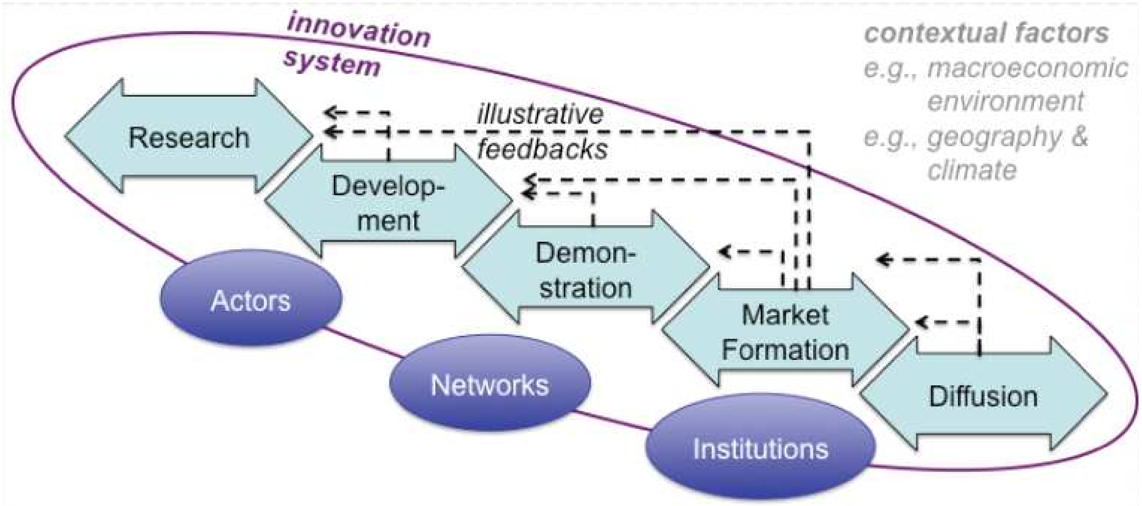

Figure 1. Chain-linked model of innovation system (Grubler et. al 2011).

Energy-Technology Innovation Systems

We have until now discussed innovation systems in general, without specifying the economic sector in which these processes are occurring. Bearing in mind the many energy-related challenges that affect sustainable prosperity (e.g. energy for economic growth, air and water pollution, energy poverty, deforestation, climate change), the focus of this paper is primarily on energy-technology innovation in developing countries. As such, we shall now focus specifically on the *energy-technology innovation system* (ETIS), which applies the innovation system model to the energy system (Grubler et. al 2011).

National energy-technology innovation systems vary and each country will have a unique set of goals for its ETIS. Energy innovation systems can be used to improve existing technologies through cost reductions, enhanced efficiency or incentives to diffuse existing technologies (Socolow and Pacala, 2004). Countries may prefer to place primary emphasis on invention of new breakthrough technologies via an emphasis on basic and applied energy-technology research (Hoffert et al. 2002), though this would be difficult for many developing countries.

From a normative perspective, there is an essential caveat that must be stated: The outcomes of the innovation process are irreducibly uncertain. It is not possible to guarantee that X policy for innovation will lead to the development of A technology, or the diffusion of B technology into the system. There is inevitable and unavoidable complexity within this system, and the context-dependency of the entire chain-linked model process only exacerbates this fact.

Nonetheless, case-based observations are useful in developing a more fundamental understanding of the systems of innovation. Empirical data and analyses all support not only the energy technology innovation system approach, but also highlight the central role of innovation in sustainable development.

In order to present a brief overview of the key components of an ETIS, we will first highlight the stages of the innovation-system as it applies to energy-technology innovation and the processes that are necessary to advance a technology through the system. Then, we will discuss the external "forcing" roles of actors, institutions, and energy-policies in shaping the energy-technology innovation process.

Stages and Processes of Innovation in the ETIS Model

As identified in Figure 1, the stages of energy-technology innovation are research, development, demonstration, market formation, and diffusion. In this context, "market formation" is included because many cleaner technologies fail to transition from demonstration to diffusion not necessarily because of technological problems, but because they are too expensive, too difficult to integrate into existing systems, difficult to scale-up, or because of an apparent lack of market demand. The role of government in the market formation stage can be critical to overcome these various barriers to diffusion of cleaner technologies.

Within the context of the ETIS model, Jacobsson and Lauber (2006) identified seven key processes as necessary to the progress and maturation of an energy technology. Government policy is needed at every stage, and to catalyze interaction among the stages, but when to intervene, and how much, remains a contentious debate.

The first process is entrepreneurial experimentation. Because the process of innovation at all stages requires risk-taking, entrepreneurship is essential to cope with the large uncertainties surrounding new combinations of technological knowledge, applications and markets (Meijer, Hekkert 2007).

The second process is knowledge development, involving both knowledge generation and learning. In order to be effective, a robust program for research and development must be accompanied by a robust knowledge network, which aids in the learning process and the dissemination of knowledge, including across national borders (Carlsson, Stankiewicz 1991).

The third process is targeted research. At a minimum, the limits of the energy technology innovation system might appear to be boundless. New technologies that are physically impossible to obtain can be imagined on the backs of envelopes. In order to guide the process of knowledge development, guidance functions are essential, and can be provided by actors, institutions, networks or policies.

The fourth process that can be targeted by energy policies is market formation. As discussed in the above sections, crossing the valley of death from demonstration to deployment is one of the most difficult stages for an emergent technology (as is going from R&D to demonstration). The creation of "niche" markets (Kemp, Schot & Hoogma 1998), through subsidies and financial incentives is thus a good example of market formation.

The fifth process is the mobilization of capital resources, including financial, material and human capital, into the innovation system. None of the stages of the innovation process for energy technologies can occur without defined methods for the mobilization of resources from public or private sources.

The sixth process that is essential to an effective ETIS is somewhat ineffable. Within the innovation process, there are many stages in which structural, institutional or mental barriers to change must be overcome or eliminated. There may be financial interests directly opposed to innovation, or "within the box" thinking that must be overcome. Thus, an institutional system that allows for lobbying by multiple interests, civic engagement, advocacy, and institutional dynamism can also be helpful.

The final key process is related to the final stages of effective energy technological innovation and essentially boils down to "making the vision real." Materialization, or reification of the up-scaled deployment of the energy technology often requires particularly targeted policies for effective achievement.

Policies for ETI

The above seven processes can be targeted by government energy policies, public institutions, or private actors since they all shape the energy technology innovation process (see Figure 1). It is possible to analyze the performance of a particular innovation system if the appropriate metrics can be identified. One can, for example, compare the resources spent on energy technology RD&D, the subsidies that exist for market formation, or the amount of venture capital investments at different stages of the innovation process. Comparative case studies, such as those presented in this paper, also offer a complementary and useful tool for energy-technology innovation assessment. Within case studies, the relative role of public and private actors, and the role of institutional innovations in shaping the effectiveness of policies, all require consideration.

Broadly, policies for ETI can be divided into policies that can: (i) directly target the innovation process; (ii) support the innovation system as a whole; or (iii) unintentionally impact innovation while targeting an unrelated matter. An assessment of policies for energy-technology innovation in developing countries can take all of these forms since policies can attempt to direct investments to particular research, or incentivize particular actions. Examples of these policies are shown at the top of Figure 2. Additional policies that target institutional organization, the exchange of knowledge, and the diffusion of processes and practices are also required to make sure that the system functions smoothly. Examples of such policies are given at the bottom of Figure 2. Finally, the environment for innovation is the product of general policies for market regulation, education, and tax structures that operate at all levels of the economy and are not particularly targeted towards innovation. These policies can be understood as part of the context in which the innovation system is situated, but also as policies that can, and in some cases must, be adjusted in order to encourage effective energy-technology innovation.

A comprehensive review of different kinds of energy-technology innovation policies is beyond the scope of this paper (see Grubler et. al 2011). However, it is essential to highlight key properties of policies that can shape their effectiveness. One of these is the stochasticity of public investments in energy, which are often pulsed into a system, rather than steadily injected. Effective innovation requires sustained and steady "inputs" – people who are able to focus over the longer term on improving or inventing energy technologies. Adequate and stable financial resources are also required for this to be successful (Gallagher et al. 2006).

Another such property is particularly applicable to our consideration of the case of innovation in developing countries, namely the existence of international spillovers and feedbacks within energy technology diffusion. While many may believe that a general model in which developing countries can engage in technology "leapfrogging" exists, this process is not actually general, and is *certainly not automatic. Instead, the ability of developing countries to engage in leapfrogging is a function of appropriate ETI policy frameworks*. It is *conditioned* on the development of a certain level of absorptive capacity and appropriate policy and market incentives for technology diffusion in the recipient country. An example can be seen in the development of China´s automobile industry. There the government provided support for firms to purchase new technology through licensing and joint ventures, but initially failed to encourage the adoption of pollution-control technologies because pollution-control standards were not in place until 2000. Thus, while there was rapid leapfrogging for the automotive industry generally, no leapfrogging occurred with regards to pollution-control technology until the appropriate environmental policies were in place to incentivize its diffusion. (Gallagher 2006b and 2006c).

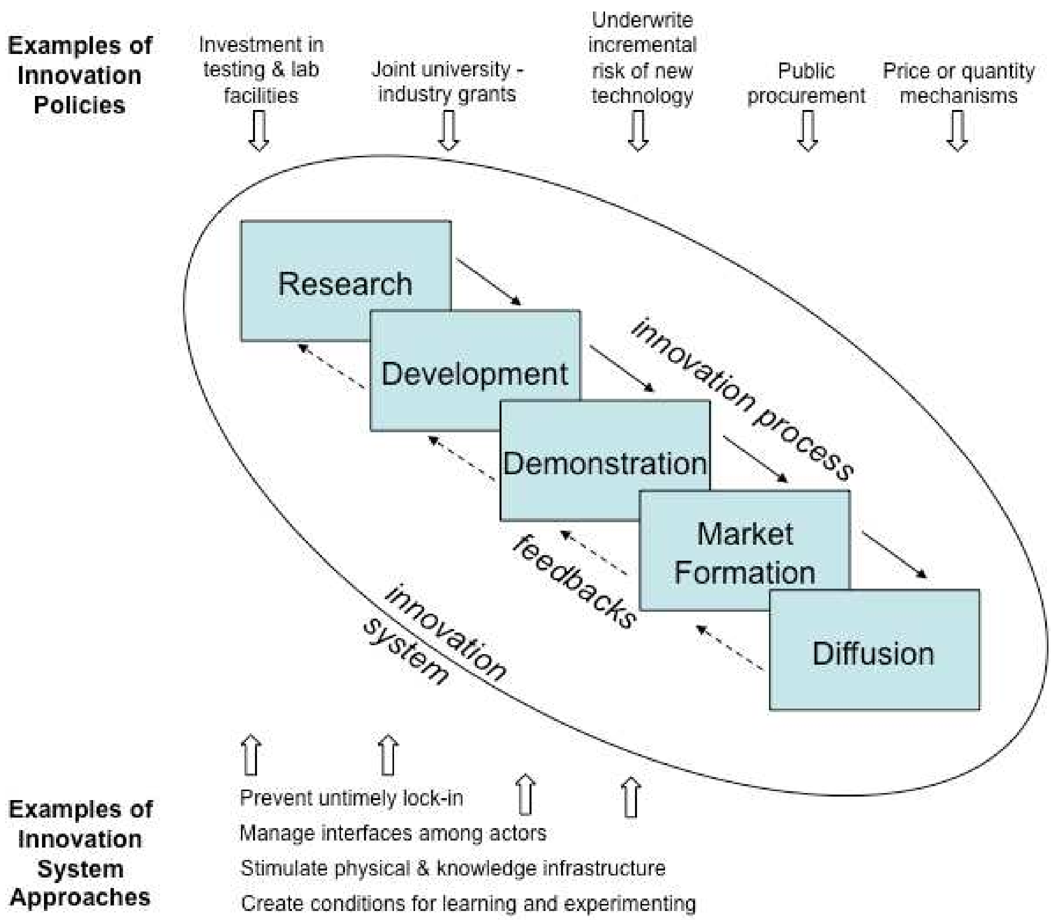

Figure 2. The Role of Policy in the Energy Innovation Process (Grubler et. al 2011)

Innovation Systems in Other Sectors: Agriculture

The above section has presented a framework for understanding the innovation system for energy-technologies as well as the role of energy policies in shaping this process. While energy-technology innovation is the primary focus of this paper because of its salient role in enabling sustainable prosperity and pathways towards a green economy, it is also important to discuss the innovation systems involved in other sectors that relate to sustainable development, such as agriculture. While the frameworks for understanding innovation systems presented above are likely to hold in general, a discussion of the particular details of another sector is merited.

Innovation processes in the agriculture sector experienced a profound shift in the latter part of the 20^{th} century once the inadequacy of policies which assumed that the diffusion of new agricultural techniques would naturally take place across agricultural circumstances and even across countries became apparent (Ruttan, 2001). For the United States, the old “land-grant” model of research universities increasingly gave way to the entrepreneurial university engaged in biotechnology research in association with the private sector (Etzkowitz 2001). Etzkowitz argues that this change was actually a process of iterative feedbacks in which new technologies such as genetic engineering and biotechnology, as well as new advances in computer science forced research and development institutions to adapt with innovative organization. This process has further increased research into the same areas that precipitated the structural shift in the first place. Interestingly, this has all taken place against a background of relatively assured, but static government investment in agricultural RD&D. Sunding and Zilberman (2001) explain that “the evolution of biotechnology suggests that the university is becoming a major player in industrial development, and it affects the structure and competitiveness of industries.” (Sunding and Zilberman, 2001).

While the agricultural innovation system functions largely similarly to the generic innovation system model shown in Figure 1, the structure of the agricultural sector has obvious influences on agricultural-technological innovations that are unique to the sector. Innovation in this sector can occur both at the “upstream” end, which is more technologically driven (fertilizers, seeds, machinery, production technology) and at the “downstream” end, which is more organizationally driven (development of agro-industries, new forms of global marketing). Significantly different resource pools are required for these different types of (private capital, public institutions, cooperative R&D, and frameworks for learning and diffusion) (Possas et al. 1996). For developing countries, Hall (2005) argues that capacity building in for sustainable agricultural development requires the need for *diverse* innovation systems, and suggests policy approaches which attempt to integrate different established innovation systems at strategic points in time (Hall, 2005).

Because of the nature of the agricultural sectoral context, there are particular issues related to the diffusion of agricultural technologies that have been identified in the innovation process that distinguish agriculture from some forms of energy technology diffusion. In particular, because the agricultural sector involves both large private industrial actors and many small rural land-holders, the role of knowledge-sharing and policies for diffusion of innovation have a profound impact. As Calestous Juma points out, within agricultural innovation systems in developing countries, it is not enough to establish research and development programs at universities. Because farming practices are tied directly to community governance networks, new technologies must be able to be absorbed by these networks. This sometimes leads to "innovative" policies, which seek to return to more traditional practices of management, such as the reintroduction of Vayalagams to manage community water resources for irrigation in rural India (Juma, 2011, 76).

Because agriculture must adapt to a changing climate, agricultural innovation systems are faced with an even greater challenge (Juma, 2011). Knickel et al. (2009) argue that,

> Innovation policy is a key to competitiveness, a sustainable use of natural resources and integrated development of rural areas, and, more specifically, the structural changes required for the development of a low-carbon bio-economy and the adaptation of (agricultural) production systems to the foreseeable changes in climatic conditions. In order to successfully implement an effective innovation policy, existing knowledge systems and knowledge brokerage processes have to be renewed and more effective, novel approaches institutionalized. Innovation services and agencies need to be able to encourage the active development of new value added markets, products and services.

The Importance of Ecosystem-Services Valuation

The discussion of innovation within the agriculture sector also serves to highlight the importance of innovation in other aspects of sustainable development. A full consideration of energy-technology innovation requires placement of the system within the context of the ecosystems in which it is situated. In terms of the development of a green economy, a recent report by UNEP suggested that ecosystem-service valuation is a key component of sustainable development (UNEP, 2010). While the need for consideration of these services in relation to the agricultural sector's innovation system is clear, all innovation systems are likely to require institutional innovations and organizational changes in how knowledge is transferred and technologies are deployed, that take into account feedbacks to ecosystem services.

IV. Typological Frameworks

Categorization of Developing Countries

Categorizing developing countries according to their capacities for technological innovation is an inexact science. This is because the diversity of developing country circumstance is compounded by the fact that no single indicator of "innovative capacity" exists. Still, the processes and stages of innovation presented in the previous section provide a useful basis for a categorization of innovative capacity within developing countries; namely, if a developing country has an established capacity for all of these processes, than its innovative capacity will be more robust.

Measuring or assessing these capacities is not easy. In many cases, it is difficult to determine a good quantitative metric for measuring "institutional capacity" or the degree of "market formation" within a country. Where quantifiable statistics present useful proxy indicators, as for example in the amount of investment in research and development, many of the data are difficult to find or completely lacking for many developing countries (Gallagher et. al 2011). This "data challenge" only becomes more difficult with finer attention to the details of the indicators (i.e. investment in basic research or applied research, public vs. private vs. state-owned enterprise). Nonetheless, a coarse typological framework is advanced in this paper, as is shown in Table 1.

Table 1. The six categories for innovative capacity in developing countries are drawn from the seven processes of innovation in the ETIS model, with the last two processes of barrier

breaking and materialization redefined as “institutional capacity.” Possible indicators that could be used to rank countries on the basis of these categories are listed, but are necessarily incomplete. Data for many of these indicators in most developing countries are non-existent, difficult to quantify, or involve substantial subjective decisions. See text for discussion.

Categories of Innovation Capacity	**Possible Indicators of Capacity**
Entrepreneurial Experimentation	• Amount of venture capital investment • Number of industries and processes invented • Frequency of licensing of “spin offs” from universities • High-tech IPOs
Knowledge Generation	• Percentage enrollment in primary and secondary education • Literacy Rates • Percentage enrollment in higher education • Number of scientists and engineers • Patents and published citations in science and engineering
Targeted Research	• Amount of public investment in R&D • Amount of private investment in R&D • Extent of patents and citations • Existence of partnership vehicles for public/private partnerships
Market Formation	• Existence of policies, subsidies, financial incentives • Ability to enforce implemented policies (e.g. protect intellectual property
Mobilization of Capital	• Interest rates • Access to loans and finance
Institutional Capacity	• Total factor productivity (for measurement of efficiency?) • Existence of policies, subsidies, financial incentives • Targeted interventions

In order to compare across developing countries, we translated these categories and indicators into the conceptual graphical framework shown in Figure 3. This allows for comparisons of countries by each indicator (shown on each ray from the origin) and across all six categories of innovation capacity, which provides a more general comparison of the innovation capacity across countries. Figure 3 also presents areas for government officials to focus upon, i.e. if a country is “skewed” in its capacity or found to be lacking in one category or another, than officials might want to consider focusing on that area.

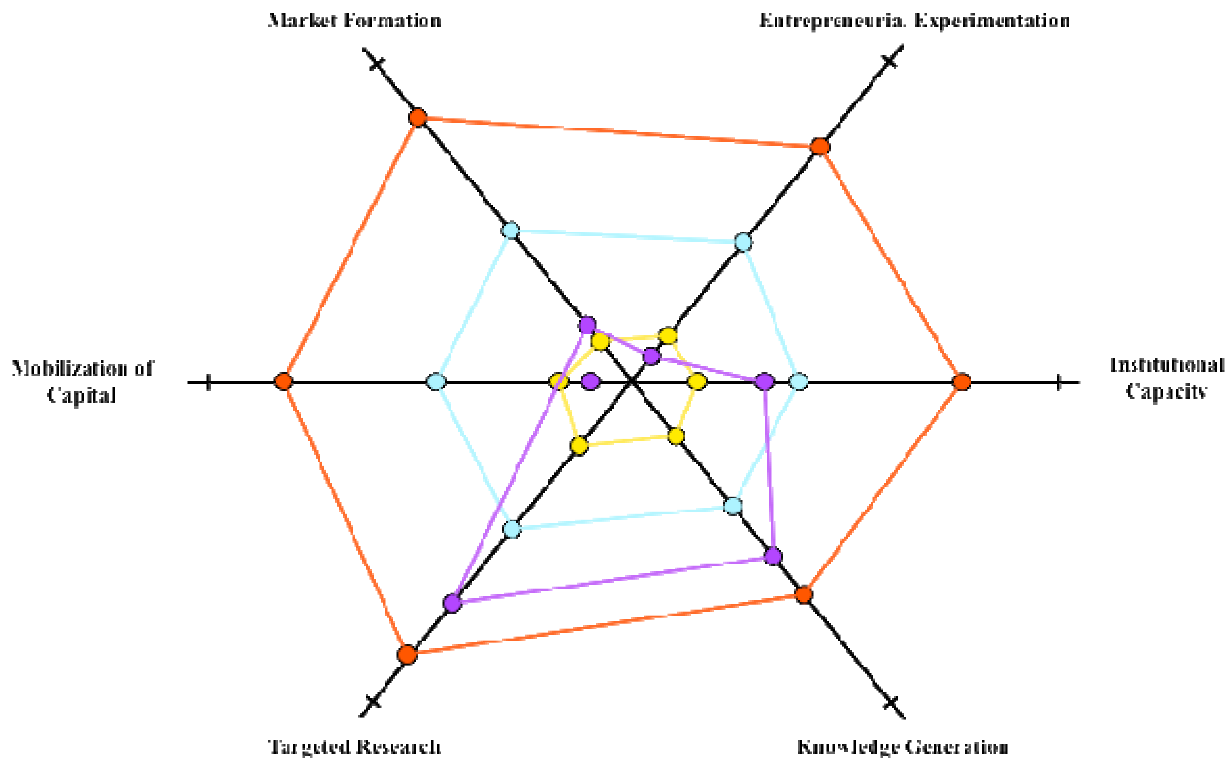

Figure 3. Conceptual framework for categorizing capacity for innovation in developing countries. Innovative capacity is divided into the six categories of capacities presented in Table 1, with each capacity on a scale starting at the middle of the diagram, and increasing outward. Four idealized "archetypes" of developing country are shown. A "core" country (shown in yellow) has low innovative capacity across all categories. A "middle" country (shown in blue) has moderate innovative capacity across all categories. An "expansive" country (shown in red) has developed capacity for innovation across all categories. Finally a "skewed" country (shown in purple) has highly developed capacity for innovation in some categories, with low capacity in other areas.

Because of the difficulty in obtaining data for all developing countries, and because of the subjectivity involved in a) selecting an indicator to represent a category, and b) assigning a value to that indicator when no reliable data exist, a full comparative analysis of developing country innovation systems is beyond the scope of this paper. However, in order to provide an illustrative example, Appendix 1 includes a "sketch" of what a comparison might look like, and gives a sense of the way in which this typological framework could facilitate both comparative analysis and targeted policy development. Better data sets and more robust indicators are required.

Key Factors Affecting Innovation System In a Country

The innovation capacity of a developing country is undergirded by a variety of factors that policy makers must consider. One such factor is geography, which can include both physical human geography (proximity to other countries, coastlines, ports, extant major urban centers), as well as cultural geography: linguistic, religious, historical, or other cultural factors. Geographical factors may be beyond the policy-scope of a country to influence, but because of their role in shaping the potential innovation policy landscape, they are included here.

Second, a country must consider its natural resource endowment. When doing so, countries must survey their nonrenewable and renewable resources. Focusing solely on nonrenewable resources might preclude opportunities for growth and create negative feedbacks within the economy. Indeed, the Resource Curse Hypothesis asserts that countries with extensive (nonrenewable) natural resource endowments have experienced lower levels of economic growth than countries with lower levels of natural resources (See Sachs and Warner 1995, Constantini et. al. 2007). We therefore employ a broader definition of natural resource endowment that includes renewable sources such as geothermal, wind and solar. As the case study below makes clear, Bangladesh has built a thriving renewable energy sector built on its most bountiful renewable resource: the sun.

Third, a country must leverage its human capital. The knowledge generation category provided above delineates a variety of metrics ranging from school enrollment to literacy rates and the number of scientists and engineers within a country. Deciding which of these metrics to focus on is, of course, highly contingent upon the structure of each country's economy and its position as a core, middle, expansive or skewed country. For example, the vast majority of field engineers who sell, install and maintain the off-grid solar home systems in Bangladesh received a Diploma in Engineering (Personal Observation). The Diploma in Engineering programs across the country are overseen by the Bangladesh Technical Education Board (BTEB), which was established to "organize, supervise, regulate, control and develop technical and vocational education" across the country in the 1960s (Bangladesh Technical Education Board 2011). Thus the establishment of a standardized technical and vocational infrastructure 50 years ago to address the lack of trained technical personnel within the country has allowed for tremendous innovations to take place within the off-grid solar PV industry. Indeed, many of the women trained as Diploma Engineers who work in the off-grid solar industry train less educated women how to construct and repair component parts of solar PV systems, which creates a cascading effect down to less educated sectors of society. Much like Bangladesh, China has a strong tertiary technical education system. Because the Chinese solar PV industry is focused on the export market, however, it needed to bring Chinese nationals who received their PhDs overseas back to the Mainland to run the nascent firms. As will be discussed in detail below, in both

Bangladesh and China, the presence of a large group of technically trained individuals allowed firms to leverage their for comparative advantages to create dynamic, innovative and nimble firms.

Fourth, energy development and output require energy services. The industrial, agricultural, transportation and building sectors are reliant upon significant energy inputs. Lowering the amount of energy required per unit output reduces the cost of producing goods, decreases the amount of additional capacity needed within the electricity sector and reduces greenhouse gas emissions—all of which promote sustainable development. Countries should focus their attention on the sectors of the economy in which they have a competitive advantage for which reduces energy inputs would make the sector even stronger.

Fifth, energy-technology innovation requires the support of the private and public sector, as discussed earlier. Private sector firms will innovate when they perceive a market need or develop a new product aimed at expanding a market sector. However, private firms do not have the assets necessary to engage in expensive and long term basic research projects that might not generate marketable products. Funding this basic research is a crucial role played by governments. In addition, government policies that correct for market failures that do not account for externalities are necessary to encourage sustainable technology innovation.

Finally, innovation requires market formation, the mobilization of capital and overall institutional capacity. While all of these categories exist along a spectrum, there is a minimum threshold that must be achieved in order for an innovation system to flourish. Broadly speaking, there are two types of innovations: new technologies and improved processes related to existing technologies. For the former, the ability to enforce intellectual property rights is vital to creating an environment in which firms are willing to invest in RD&D. RD&D, in turn, require finance, which is cheapest and easiest to access in a country with strong financial markets and stable interest rates. Finally, many technologies become stranded in the "valley of death" between development and deployment because of a lack of clear, strong and predictable policies and subsidies. The feedbacks between all of these processes make it hard to determine a minimum threshold required for new technologies to be developed. In regards to process innovations, intellectual property rights might be less important, but access to finance and a favorable and predictable regulatory environment remain vital. Strengthening any of the abovementioned categories of innovation capacity will make the environment more conducive to innovation.

V. Case Study: Off-Grid Solar in Bangladesh

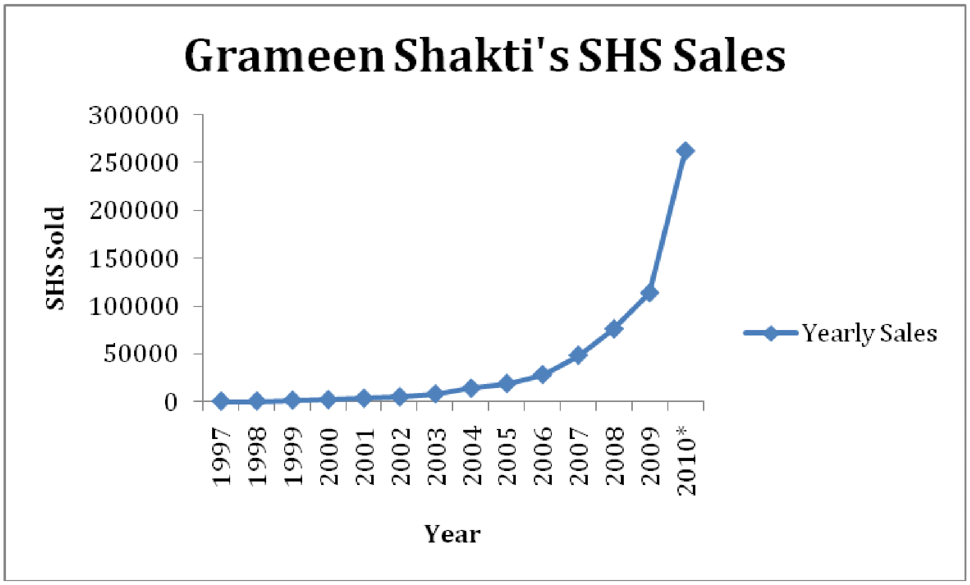

Figure 4: Yearly Sales By Grameen Shakti: 1996 – 2010

* The total sales number for 2010 were derived by extrapolating from January to August data under the assumption that monthly sales were constant throughout the year. (Source: IDCOL, 2010)

The off-grid solar PV sector in Bangladesh provides an example of a country leveraging its comparative advantages to create an innovative and replicable solution to expanding energy services to the 1.5 billion people who live without electricity across the globe. Since the first solar home system (SHS) was purchased in 1996, more than 650,000 have been sold to off-grid customers through the use of microfinance. SHS are stand alone DC power supply systems that include a solar panel, charge controller, and battery that allow the owner to operate appliances such as lights, mobile phone chargers, radios and televisions (Meyer 2004). These systems provide energy services that improve health outcomes (Fan and Zhang 2001), increase the amount of time that children study and facilitate the growth of home businesses (IDA 2010). Applying the models put forth above to the growth of the off-grid solar industry in Bangladesh provides insights into how other countries can innovate their way to sustainable prosperity.

The growth in off-grid solar home system sales was driven by (i) ample sunshine; (ii) a pre-existing infrastructure of microfinance institutions; (iii) a technically trained population; (iv) the superiority of solar pv over kerosene; and (v) the support of domestic and international institutions. The consistent sunshine and high level of overall solar irradiance make Bangladesh an ideal location for solar photovoltaic technology. The average solar irradiance in Bangladesh varies from 3 to 6.5 kWh/m^2 throughout the year (Sarkar et. al) and the Asian Development Bank has estimated that solar pv could produce 50,463 mWh of electricity annually (Mondal et. al). In order to harness this potential source of electricity for rural households, a cost-effective deployment system needed to be created.

Creating such a system required entrepreneurial experimentation, which has a long and successful history in Bangladesh. Indeed, microfinance began in Bangladesh when Dr. Muhammad Yunus supplied to first-ever Grameen Bank loan to 42 stool makers in 1976 (Yunus 1999). Since then microfinance institutions have proliferated and there are currently 30 million microfinance borrowers with a collective $2.2 billion in outstanding loans in Bangladesh (Kazmin, 2010). In 1996, senior officials at the Grameen Bank founded Grameen Shakti, which aims to provide renewable energy technologies in rural Bangladesh (Barua 2009). Grameen Shakti used the Grameen Bank's expertise with microfinance and rural consumers to address the fact that 80% of rural households lacked electricity (Bangladesh Bureau of Statistics, 2009) through the sale of SHS with microfinance. The founders of Grameen Shakti applied their expertise to a social need in a novel and inevitably effective manner.

The selection of SHS by Grameen Shakti was astute. Solar home systems provide approximately 100 times more light than do kerosene lamps (the primary lighting source) without the related indoor air pollution, noxious odors and soot (Asaduzzaman et. al, 2009). The improved output of light makes it easier for students to study and other family members to partake in income-generating activities after dark. Moreover, solar home systems can power appliances—a tremendous benefit over kerosene lamps. The relative advantage of SHS over kerosene make it an appropriate technology for rural Bangladesh.

Despite the appropriateness of the technology, the population's familiarity with microfinance and the abovementioned existed of a large group of Diploma Engineers, initial sales were sluggish. Sales began increasing in 1998 following: (i) the government's decision to lift the import duty and value added tax on solar photovoltaic panels (Islam 2002); and (ii) Grameen Shakti's securement of an International Finance Corporation/Global Environment Facility loan that allowed it to extended the payback period for customers to 36 months (Martinot 2000), both of which increased the institutional capacity of the sector. Moreover, the IFC/GEF loan lowered the amount of money customers had to pay for each monthly installment, which dramatically increased the number of potential adopters. Indeed, the extension of long-term credit to consumers relied on the effective mobilization of capital.

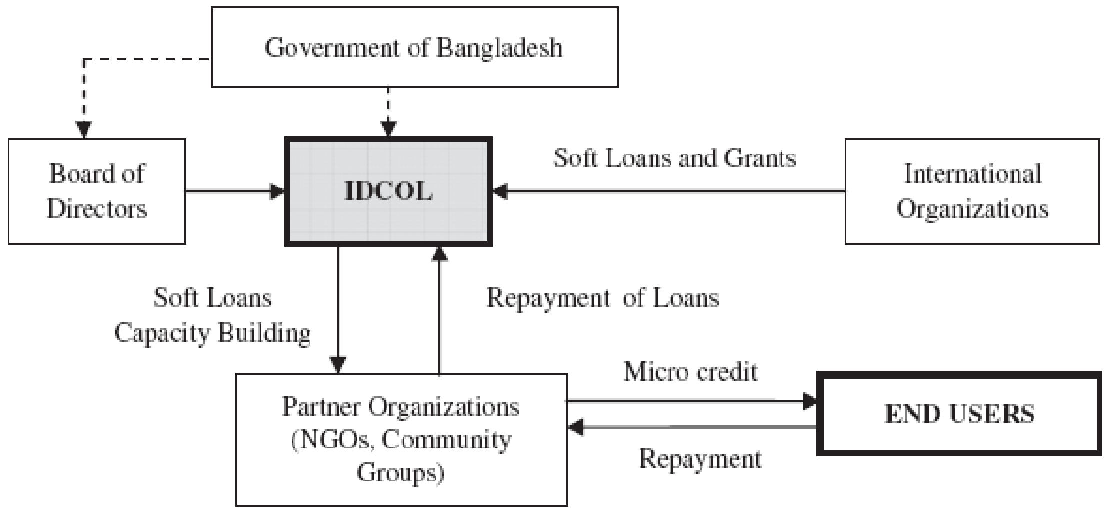

Figure 5: This graphic provides a diagrammatic representation of the institutions involved with the sale of SHS under the auspice of IDCOL. (Source: Uddin and Taplin, 2009).

The *ad hoc* support of off-grid solar by the Government of Bangladesh and international organizations coalesced into a formalized program following the establishment of the World Bank-financed Rural Electrification and Renewable Energy Development Program (RERED) on December 31, 2002. The project aimed, *inter alia*, to finance the sale of 50,000 SHS to off-grid customers by extending grants and soft loans to the Infrastructure Development Company Limited (IDCOL), a non-bank financial institution established by the Government of Bangladesh in 1997 (IDCOL 2008) (see Figure 1). IDCOL passes these savings on to customers by offering the Partner Organizations that sell SHS buy down grants, institutional development grants and refinancing for each SHS they sell. The Partner Organizations are only eligible for the grants following their approval by IDCOL and are required to sell components that are approved by the Technical Standards Committee that includes experts from IDCOL, the Rural Electrification Board, the Local Government Engineering Department and the Bangladesh University of Engineering and Technology (IDCOL 2007).

RERED achieved its goal of selling 50,000 SHS in August 2005 and financed a total of 320,000 SHS by the time the project ended in December 2009 (World Bank 2009). This success was partially attributable to the growth of approved Partner Organizations from five when RERED began to 23 by June 2010 (Husain 2010). The ability of new participants to enter the market after going through a rigorous screening process ensured that the quality of the products and services would not suffer as the market expanded. Indeed, the World Bank has renewed the project through the end of 2012 and set a target of installing an additional 300,000 SHS (World Bank 2009). The integration of non-profit, government and international organizations stimulated the exponential growth in off-grid SHS sales.

The off-grid SHS sector has created thousands of jobs and unleashed new income-generating possibilities for people in rural Bangladesh. For example, shop owners who install a SHS report increased sales revenue because the improved light from SHS attracts more customers. In addition, many households and businesses generate income by charging people a small fee to charge their mobile phone off of the electricity generated by their SHS. Grameen Shakti employs more than 7,500 individuals, the vast majority of whom are field assistants that sell, install and provide maintenance services related to SHS (Grameen Shakti 2010). In addition, Grameen Shakti operates 45 Grameen Technology Centers run by women engineers that maintain, repair and assemble the electronic parts of SHS. These centers train and employ underprivileged rural women who generally lack access to other income-generating opportunities. Thus far these centers have trained more than 3,000 women (Kamal 2010).

The growth of the off-grid solar sector in Bangladesh has facilitated the growth of domestic companies engaged in ancillary services. For example, Rahimafrooz sold the lead-acid batteries for 75,000 SHS in Bangladesh and over 80,000 for PV systems abroad in Nepal and Bhutan by 2006 (Ashden Award 2006). In fact, with the exception of tube lights and solar panels, all of the component parts of SHS are manufactured in Bangladesh. This is about to change as Rahimafrooz Renewable Energy plans on set up the first solar panel assemble plant in Bangladesh to take advantage of the growth in off-grid SHS sales (Parvez 2009) and recently signed a memorandum of understanding with TATA BP Solar to install a 5 MW Solar power plant (The Daily Star 2010). In just 15 years, Bangladesh has gone from selling its first SHS to having the capacity to manufacture almost every component of the systems domestically.

Lessons for Other Countries

The growth of off-grid SHS sales in Bangladesh provides many useful insights for policy makers interested in building successful renewable energy sectors in other developing countries. The innovation in Bangladesh is primarily a *process* innovation. The technology (solar PV) and the mechanism for its diffusion (microfinance) existed, but no one had put them together. Although this combination might seem obvious in retrospect, the pairing did not yield significant results immediately. In fact, sales did not grow significantly until the sector integrated the specialties of non-profits (consumer knowledge and entrepreneurial experimentation), international organizations (mobilization of capital and institutional capacity), the government (institutional capacity and market formation) and academics (technical standards and market formation) in 2003. As Figure 1 shows, sales started growing following the introduction of RERED in 2003 and took off around 2006.

Unlike China, Bangladesh did not have the resources to create a world-class industry quickly; rather, the off-grid solar industry is beginning to yield big returns 15 years after the first system was sold. The time lag between the genesis of the off-grid solar sector and its large scale impact being felt was long, and countries need to be willing to accept small and incremental gains. Over time, small gains begin to look bigger as the magnitude of the sector grows, but these small gains can only gather momentum if policy makers have a long term time horizon in mind.

VI. Case Study: Solar PV in China

The development of the solar PV industry in China is a case of rapid clean energy acquisition, assimilation, and manufacturing. It is also a case of development of a vibrant clean energy industry in a short period of time, and of rapid "learning" in the sense that the prices of solar PV modules have fallen dramatically in just a few short years. It is not, however, a case of widespread or rapid deployment of clean energy technologies in the domestic market. Indeed, 98 percent of China's solar PV modules were exported as of 2008 (de la Tour 2011). Grid-connected solar PV is very small in China at 0.4 GW, representing a tiny fraction of China's energy supply, which reached 874 GW in 2009 (China Electricity Council 2010). Compared with the growth in deployment of other forms of energy in China, solar is a distinct laggard. The main reason that solar has not made a stronger dent in China's domestic market is that the government has failed to put in place strong enough policy incentives to encourage the production and use of solar energy due to the relatively high cost of solar (Ma et. al 2010). In contrast, the Chinese government has strongly supported the deployment of wind energy domestically, adding 13.8 GW in 2009 alone – more than any other country in the world (REN21). In 2009, China's domestic demand for grid-connected solar PV was only 160 MW, compared with Germany's market of 3800 MW that same year (Martinot 2010).

Instead, Chinese solar PV manufacturers are taking advantage of solar PV markets in places like Germany, Italy, Japan, and the United States, where governments are more aggressively supporting the deployment of solar energy. In 2009, China produced 40 percent of the world's solar PV supply (REN21 2010), growing from only 15% global share in 2006 (Martinot 2010). The average annual growth rate for Chinese solar production capacity between 2000 and 2006 was 70 percent (Marigo 2007). The top three Chinese producers are currently Suntech (705 MW produced in 2009), Yingli (527 MW) and JA Solar (504 MW) (Martinot 2010).

An overview of the policy environment

The Chinese government has expressed strong support for the development of renewable energy in China. China already has the largest solar hot water capacity of any country with 70 percent of total global capacity (REN21 2010). The Chinese government passed the Renewable Energy Law in 2005, and it set a national renewable portfolio standard (which was later revised) to 15% of final energy by 2020, and 20 percent by 2020 for the electricity sector. In 2010, the government revised the Renewable Energy Law, which creates a guaranteed but differentiated purchase regime for various forms of renewable energy. For utility-scale solar PV (multi-MW), the government established a modest feed-in tariff of RMB 1.09/kWh (approximately 16 cents/kWh). The government also established a solar PV subsidy program called the "Golden Sun" program in 2009. Under this program, off-grid installations receive 70% capital subsidies and grid-connected (>300kW) installations receive 50% capital subsidies. Installations are limited to 20 MW per province. In addition, the Ministry of Finance and Construction provides subsidies of 15 RMB/W for grid-connected solar PV and 20 RMB/W for building-integrated PV for installations that are 40 kW or larger. These projects must also utilize solar PV modules of minimum specified efficiency levels. The government also created a new solar PV bidding program, which establishes benchmark tariffs on the basis of competitive bidding for specific quantities of PV. At the provincial level, two provinces have also established preferential tariffs for solar PV (Martinot 2010).

Reflecting the relatively high costs of solar PV, the Chinese government's draft targets contained in the 12th Five-Year Plan for renewables are 300 GW of hydro, 150 GW of wind, 30 GW of biomass, and 20 GW of solar by 2020 (REN21 2010). Another form of government support for renewables is overall industrial policy for the renewable energy industry, which is discussed in the next section.

The development of a new industry

The Chinese solar PV industry burst upon the global scene around the turn of the century, and like other Chinese industries, expanded extraordinarily rapidly after 2000. Much of the credit for the expansion of the solar PV industry goes to the firms themselves, but they also received support from the government. The exact nature and extent of this government support is a source of much controversy. The United Steelworkers of America, for example, filed a case with the Obama Administration in September 2010 accusing China of violating World Trade Organization rules by subsidizing the export of clean energy technologies.[1] A 2010 series of articles by Keith Bradsher of the *New York Times* asserted that China provides generous subsidies to the clean energy sector in the form of low-interest loans or provision of below-market prices for land. Specific to solar energy, Bradsher writes that "near zero" interest rate loans were provided to the solar PV industry. Another way of looking at such subsidies is to notice that by providing support to the industry, which in turn has been able to greatly reduce the global market price of solar PV, the Chinese government has used its own taxpayer dollars to bring the global cost of solar down, which benefits consumers everywhere. As Mayor Michael Bloomberg recently noted, "Let me get this straight. There is a country on the other side of the world that is taking their taxpayers' dollars and trying to sell, subsidize things so we can buy them cheaper and have better products, and we're going to criticize that?" (Bradsher 2010a). Indeed, the U.S. government and other industrialized countries provide subsidies to their firms as well, including billions of dollars in loan guarantees, tax credits, and research grants (Gallagher and Anadon 2010).

Shi Zhengrong, CEO of Suntech, China's largest solar PV firm, flatly states that Suntech has received no support from the government (personal interview 2010). Zhang et. al (2009) note that the Chinese government supports solar PV generation through the State Technical Problem Tackling Plan, the "863" high-tech R&D program, and the industrialized development and key equipment "special item" programs. In addition, the government pushed for localization and domestic manufacturing of components in the renewable energy industry. China removed its local content requirement for wind turbines in 2009 (after virtually all components were

[1] In December 2010, the U.S. Trade Representative (USTR) announced that the United States had requested consultations with China under the dispute settlement provisions of the World Trade Organization regarding a program known as the Special Fund for Wind Power Manufacturing. USTR contends that this special fund provides subsidies that are prohibited under WTO rules because the grants awarded under the program "seem to be contingent on Chinese wind power equipment manufacturers using parts and components made in China rather than foreign-made parts and components" (USTR 2010).

sourced domestically anyway), and it does not have a formal local content requirement for solar PV. But, the Steelworkers petition alleges that the government stipulates the percentage of local content when granting concessions on a case-by-case basis (Steelworkers 2010).

Technology acquisition and assimilation

Chinese solar firms have employed many strategies for acquiring and absorbing the technologies required to manufacture and sell solar cells. Notably, many of the people in leadership positions in the Chinese firms spent time studying abroad, and either returned to China to start a new firm, or were recruited to join an existing firm. Two examples are the current President and CEO of Suntech and the current Chief Technology Officer of Yingli, both of whom have doctorates from the University of New South Wales in Australia. Obvious benefits of recruiting knowledgeable leadership is that such people understand quite clearly which technologies need to be acquired, show promise, or can be rejected.

A second primary strategy employed for technology acquisition is equipment purchasing and installation from foreign providers. A great deal of the manufacturing equipment in Chinese solar PV manufacturing plants is purchased from foreign equipment manufacturers, many of whom also come to install and integrate these pieces of equipment in the factories (Gallagher 2010). For one large producer, 80% of the equipment used to produce solar cells was procured from foreign manufacturers as of 2010, most of which came from Germany (Song 2010). While Chinese equipment providers can offer their equipment at one-third to one-half the cost, so far the quality of their equipment is not very good and therefore manufacturers still prefer to source internationally.

Two typical strategies for acquisition of foreign technology are licensing technology from foreign firms or forming joint ventures with foreign firms. So far, there have been few joint ventures formed in this sector, though some other sectors in the Chinese economy (e.g. automobiles) have a much larger proportion of domestic-foreign joint ventures. One notable partnership is the one between Evergreen Solar and Jiawei Solar in Wuhan. There is evidence also of licensing of foreign technologies as well as outright purchasing of foreign firms (Shi 2010).

Finally, Chinese solar PV manufacturers are pursuing a strategy of research cooperation and joint development with foreign firms and both Chinese and foreign universities. Yingli Solar has established, for example, a research partnership with ECN of The Netherlands where twothirds of the funding for the research comes from Yingli and one-third comes from China's Ministry of Science and Technology (MOST). Suntech has likewise established a formal joint development partnership with the University of New South Wales, and indeed, one of its professors, Stuart Wenham, is also the CTO of Suntech.

Manufacturing

Most Chinese solar manufacturers are more "downstream" in the PV module production process, although some are beginning to develop production capabilities for the full process in order to become vertically integrated companies capable of ingot production and wafer production as well. The benefits of vertical integration include quality control, cost control, and avoidance of supply chain vulnerabilities. Initially, there was some de-mechanization of the manufacturing process for solar PV modules to take advantage of China's less expensive labor, but most firms are moving towards or are already using automated processes.

Learning/Cost Reductions

The exact source of the remarkable cost reductions achieved by China's solar manufacturers is still unclear. Certainly, the cost of labor is one component. Another source is an innovation in the installation procedure of the finished modules – the new procedure cuts installation time from 2 hours to 30 minutes. Because the cost of silicon has been persistently high (due in part to the increasing demand for silicon from Chinese PV manufacturers), Chinese firms also report that they have endeavored to improve the efficiency of their use of silicon (Shi 2010). The cost of silicon is 30-40% of the product (Song 2010).

Barriers

Two barriers to innovation typically cited in the literature are access to finance and protection of intellectual property. There is little evidence that access to finance has been a barrier for the successful Chinese solar PV firms. During many interviews conducted during the summer of 2010 in China, no firm acknowledged any problems acquiring finance, although one said that it was aware of other firms that had some trouble. Likewise, there is no evidence that Chinese firms have been unable to access foreign intellectual property in the literature or through interviews, either because foreign firms have refused to license or sell proprietary technology. As the CEO of Suntech states, “We have access to IP” (Shi 2010). There also appears to be no reluctance on the part of foreign researchers to cooperate on RD&D.

Conversely, there is also no evidence of IP infringement so far, but nearly every firm, Chinese and foreign express “concern” about this issue. One case of a poaching of a highly trained staff member who left after signing a confidentiality agreement, but he was successfully sued. No actual cases of solar IP infringement have been filed in Chinese courts

Many have questioned why the Chinese firms are not selling more in their own domestic market. The simple answer is that solar PV is simply not competitive with pulverized coal-fired power plants, the cheapest form of electricity in China today. Even ultra-supercritical (USC) coal plants (the most efficient coal technology available worldwide) are much less expensive in the Chinese context than solar PV. Indeed, the Chinese government is actively encouraging the construction of USC plants. A related and second answer is that government policy is needed to overcome the cost hurdle in order to create a domestic market for solar technologies. The exact form of policy incentive can vary, but most manufacturers express a strong preference for feed-in tariffs similar to those in Germany or Spain because they create the most stable and transparent subsidy. Other policy options include renewable portfolio standards, production tax credits, cap-and-trade systems, or carbon taxes. Lack of Chinese government support for the domestic market has hurt solar PV deployment in the Chinese market.

In summary, this case is a good example of the development and exploitation of good capabilities in entrepreneurship, institutions, mobilization of capital, and targeted research through joint RD&D with international partners. Rather than emphasize knowledge *generation* through R&D, the Chinese solar sector has pursued a strategy of technology *acquisition* through the variety of means discussed above. And, the entrepreneurial firms are mostly taking advantage of markets formed by the policies of foreign governments, not the Chinese government.

VII. Policy Implications

Our knowledge about innovation systems is growing, but still nascent in many respects. Much more scholarship is needed to examine the empirical evidence about how national innovation systems work, how they can be optimized, and especially how innovation systems can be harnessed for sustainable prosperity. In this paper, we have provided two short case studies about the development and deployment of solar PV technology from very different developing countries: Bangladesh and China. These cases demonstrate that even starkly different countries can develop strong innovation capabilities for sustainable prosperity, but the cases also illustrate that these capabilities will differ as a result of national circumstance and levels of effort to build up such capabilities.

As explained in Section IV, there are many kinds of capabilities that must be nurtured in order to create an innovation system that can produce new kinds of knowledge and technology to benefit society and the planet. These capabilities include entrepreneurship, effective institutions (ranging from markets to government ministries), the ability to mobilize capital, knowledge generation (which depends on many kinds of inputs including educated people and investments), and the ability to target and focus research endeavors.

Based on the review of the literature and the case studies provided in this paper, we offer a few policy implications for governments with the strong caveat that much depends on the national circumstances in individual countries, and that much more study is needed to build a large body of evidence about which policies work and don't work to accelerate or hinder innovation processes.

The first lesson is that it is important to know thyself. The strengths and weaknesses of any given industry and country provide the basis for understanding the potential competitive advantages and disadvantages of a given industry or sector. Characterize the existing innovation system – the actors, networks, institutions – as well as the existing knowledge base and resources. Once the system is characterized, identify the strengths of the system, as well as the weaknesses and gaps in the system. After such analysis, it can be determined whether or not these weaknesses can be reduced, and these gaps can be filled through policies, and if so, how.

Second, invest in improving human capabilities. With a strong primary and secondary school system, workers will be educated and able to productively contribute to new industries. With a strong higher education system, scientists and engineers will be able to more astutely acquire and modify technologies from abroad, as well as invent new products and processes at home. Whether or not the education system is weak, support students to study abroad so that they learn about different countries, approaches, and markets. They will develop networks and capabilities that will be valuable if and when they can be persuaded to return.

Third, decide on an innovation strategy, make this strategy transparently clear, and implement this strategy through government policies that are consistent, aligned, and predictable. For example, to create a market incentive for the development and deployment of low-carbon technologies, impose a modest but steadily escalating carbon tax over time. Or, establish a cap-and-trade system with multiple sequenced trading periods. Don't simultaneously provide tax breaks or subsidies for fossil fuel production, as these would be contradictory. Emphasize and facilitate feedbacks among the various stages of innovation so that information about how technologies are working in the market is fed back up the chain to scientists and engineers and vice versa.

Fourth, encourage and reward experimentation and risk-taking. Not only in the laboratory but also in the market. Help new entrepreneurs to acquire the technologies they need. Provide access to finance for these risk-taking firms. Encourage scientists and engineers in academia and companies to experiment, be bold, and to fail. Encourage collaboration between the academic and private sector.

Finally, innovation takes time, so if the goal is to strengthen or build an innovation system for sustainable prosperity, there is no time to waste.

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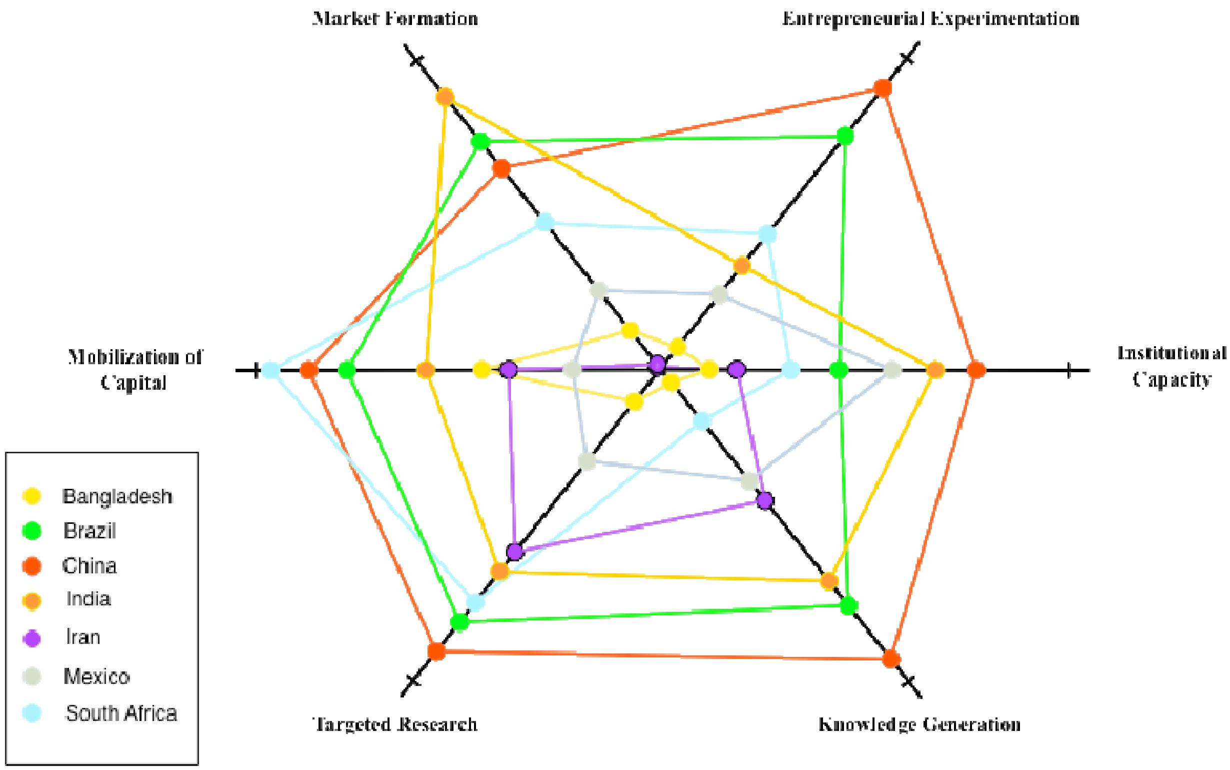
Appendix 1



This figure represents a hypothetical application of the innovation technology typological framework. The positions of each country within each category represent an approximately scaled ranking. The indicators used are shown in the table below. Although distances are not comparable across categories, the relative strengths of the different countries are apparent. For example, South Africa has strong mobilization of capital and research and development investment, but is comparatively weak on knowledge generation, while Iran lacks entrepreneurial experimentation and market formation capabilities, but has significant knowledge generation capabilities and research investments. China and Brazil emerge as innovation leaders in the developing world.

Source	NSF	UNESCO	World Bank	World Bank	World Bank
		R&D as %	Credit as %		High Technology Exports
Indicator	S&E Pubs	GDP	GDP	Licensing $	$
China	56806	1.4	126.2	10319	381345
Bangladesh	<1000	<0.2	59.4	19	96.9
Brazil	11885	1.1	101.7	2697	9140.1
South Africa	2805	0.9	172.2	1676	2010.9
Iran	4366	0.7	50.5	No Data	374.6
Mexico	4223	0.4	37.5	503	41200.6
India	18194	0.8	71.6	1578	64947.2

Sources:

Knowledge Generation: # Science and Engineering Publications

Source: National Science Board, Science and Engineering Indicators 2010

Targeted Research: Gross Expenditure on R&D as % of GDP

Source: UNESCO Science Report 2010

Mobilization of Capital: Domestic Credit Available as % of GDP

Source: World Bank World Development Indicators 2010 Report

Entrepreneurial Experimentation: New Royalties and Licensing $

Source: World Bank World Development Indicators 2010 Report

Institutional Capacity: High Technology Export $ (*PROBABLY NOT GOOD INDICATOR)*

Source: World Bank World Development Indicators 2010 Report

Market Formation: Private Investment $ in Energy Infrastructure Projects *I STRUGGLED WITH THIS ONE FOR SO LONG)*

Source: World Bank World Development Indicators 2010 Report