Leveraging Policy for Renewable Energy Development in Industrialized Countries and Emerging Markets

Amy Tang

Submitted in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy
in the Graduate School of Arts and Sciences

COLUMBIA UNIVERSITY

2013

ABSTRACT

Leveraging Policy for Renewable Energy Development in Industrialized Countries and Emerging Markets

Amy Tang

Renewable energy has the ability to play a dominate role in addressing both rising energy demand and the need for sustainable growth. Various policy measures and incentives have aided its growth in both developed and developing countries. This dissertation analyzes existing policies and financial mechanisms used to encourage renewable energy development through three academic papers. I first propose the carbon revenue bond as a new financing tool to complement the environmental credit markets that exist in developed countries. Stochastic modeling techniques are used to simulate future credit prices and determine bond value. Use of the carbon revenue bond is illustrated through three examples of wind energy projects in the European, Australian and New Jersey markets. In the absence of mature markets in developing countries, I develop the strategic structure matrix as a new framework to explain the various effects of policy measures in order to better shape future policy design. By synthesizing previous literature on how organizations are able to affect the diffusion of a new technology, the strategic structure matrix is able to deepen understanding of how policy can influence renewable energy growth. The explanatory power of the framework is demonstrated through a case study on the different paces of wind power diffusion in five Indian states. Lastly, I evaluate the Clean Development Mechanism as a tool to encourage investment from developed nations for renewable infrastructure in developing countries. I create an agent-based model to simulate investment decisions under different improvements to the program, providing quantitative

support for the effectiveness of some improvements over others. In addition to each paper’s individual contributions, the findings collectively provide important implications for the future of renewable energy policy and its ability to support continued sustainable growth.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

"Just tell yourself Duckie, that you're real quite lucky."

– Dr. Seuss

There are many people who have provided me with guidance and support throughout this journey, and to whom I owe a great deal of thanks. First, I would like to extend my gratitude to my advisor, Prof. John Taylor. He challenged all of us to continuously set the bar higher, and his refusal to accept anything but my best has made me a better researcher, thinker, writer and presenter. His genuine desire to see his students succeed makes him a great mentor and an invaluable friend. I would also like to thank Prof. Nicola Chiara for encouraging me to pursue my doctorate and guiding me through the first two years of my graduate studies, and Prof. Ashwin Mahalingam for helping me find my footing in India during my Fulbright grant. I am sincerely grateful to the members of my dissertation committee (Prof. Raimondo Betti, Prof. Patricia Culligan, Prof. George Deodatis, Prof. John Taylor and Prof. Ashwin Mahalingam) for their key insights that have made my research more meaningful to me and, I hope, to the larger academic community.

I could not have survived these past five years without laughing, commiserating, celebrating, lamenting and imbibing with my peers. To Feng Dong and Nakhon Kakkaew, thank you for making a loud and dusty mezzanine office slightly more enjoyable. To Melissa Di Marco and Hakan Unsal, for bravely forging ahead and showing all of us that, however dim, there is light at the end of this tunnel. To Wang Qi (Ryan), Sara Horsey and Aruna Muthumanickam, you made Blacksburg infinitely better with your friendship that extended beyond the office, and into the Cellar. To Josh Iorio, apologies for that first draft of that first conference paper, and thank

you for teaching me how to write. To Jiayu Chen, my endless gratitude for your patience and assistance during my battles with MATLAB and for your constant willingness to help a friend in need. To Gabriel Peschiera, for never allowing a boring moment in 618A and for your continued friendship despite differences in our student status. To Semra Çomu, for a friendship that started in New York, blossomed in Blacksburg and is continuing to Istanbul; a friendship filled with laughter and tears, and most importantly homemade Turkish food. And to Rishee Jain and Rimas Gulbinas, for being my partners in crimes in adventures around the globe, for helping me through my worst and celebrating my best. Without you two, I would have completed this dissertation much sooner.

I owe much of my sanity to my friends. While there are too many to list individually, I would like to thank them collectively for letting me escape my academic bubble once in a while, probably too often for my own good. And most importantly, I am grateful for my amazing parents, Dejun Tang (the original Dr. Tang) and Yu Gao, who have been inspirations for me. Their dedication to our family and their willingness to make the sacrifices that enabled me me to take this path are things I admire daily. I would not be who I am without their constant support and encouragement. The pride they have in my accomplishments, big or small, is often the biggest reward of all. While I haven't always listened to every word they say, I know that my greatest achievements come from listening to at least some of them.

Thank you all. I am quite lucky indeed.

For Mom and Dad,

and your unwavering love.

Chapter 1

INTRODUCTION

"Our dependence on fossil fuels amounts to global pyromania, and the only fire extinguisher we have at our disposal is renewable energy."

– Hermann Scheer (2006)

Global energy demand is rising. World population is expected to surpass 8.5 billion in 2035 and many developing countries are experiencing rapid industrial growth. Over the next two decades, energy consumption is projected to rise by 50 percent (Energy Information Administration, 2010a) and developing countries will account for 80 percent of increased electricity demand worldwide (Gupta, 2012). Meeting these needs with fossil fuels is unsustainable; resources are limited and the greenhouse gas emissions associated with burning fossil fuels have been repeatedly linked to climate change. Lowering the current level of emissions, or at the very least avoiding additional emissions, is a priority for policymakers worldwide. Generating energy from renewable sources simultaneously addresses the dual concerns of rising energy demands and the need to reduce environmental pollution. In fact, development of renewable energy (RE) constitutes 21 percent of the effort proposed by the International Energy Agency (IEA) to cut emissions in half by 2050[1] (IEA, 2008).

Great strides have been made to develop and use renewables for electricity production, heating and cooling, and transportation. In 2010, renewable sources generated 16.7 percent of total energy consumed worldwide, and wind capacity alone has increased from 6.1 gigawatts in

[1] Compared to 2005 emission levels.

1996 to 238 gigawatts in 2011 (REN21, 2012). However, as demand for energy continues to increase, particularly in developing countries where it has historically outpaced supply, there is an urgent need for greater inclusion of RE in the global energy portfolio. Unfortunately, diffusion of RE technologies has been met with several hurdles. Many countries have experienced a “carbon lock-in” of incumbent energy sources, with existing infrastructure unable to adapt past fossil fuel-based resources (Unruh and Carrillo-Hermosilla, 2006). RE infrastructure is also extremely capital-intensive with a long payback period since the amount of revenue collected during operations is small relative to the initial cost. Oftentimes, development of RE is hindered by lack of financing and difficulty attracting capital (Gupta, 2012; Liming, 2009; Masini and Menichetti, 2012). The high risk perception of newer technologies leads to a higher cost of capital compared with conventional sources of energy (Donovan and Nunez, 2012; Sadorsky, 2012), and there is no inherent financial compensation for the positive externalities of not emitting greenhouse gases. This is especially true in developing countries where other social priorities act as competition for scarce funds (Gupta, 2012).

POLICIES TO AID RENEWABLE ENERGY GROWTH

Policies have been introduced on a local, national and global scale to reduce greenhouse gas emission output and encourage development of RE infrastructure. In this section, I provide an introduction to the primary policies analyzed in this dissertation. Some programs are aimed at improving current technologies or developing new ones. Several countries have dedicated funds for research laboratories and technology centers. The Center for Wind Energy Technology in India, for example, launched several demonstration projects in three states to test the potential of wind and the machines used to harness its power in the late 1980s.

A large portion of policies have provided financial incentives to developers of RE or emissions reducing projects. Tax incentives have been popular on national and regional scales, including the Production Tax Credit in the United States, which provide tax relief to producers of renewable energy, and accelerated depreciation in India, which initially allowed developers to depreciate the full value of RE assets. These have led to the financing of many RE projects by tax investors, larger corporations able to take full advantage of the added tax benefits. Several countries also offer developers no- or low-interest loans at national or local levels to help build confidence in RE technologies and the banking infrastructure surrounding them. More assistance has been offered in the form of subsidies and grants. For example, Brazil uses an electricity surcharge on power consumers to support a fund for RE development (Dutra and Szklo, 2008). Lastly, feed-in tariffs and generation-based incentives offer a higher price to electricity produced from RE projects than conventional sources. Under a feed-in tariff, utilities pay a higher prices to buy electricity generated from RE in order to compensate for the higher technological costs and reward its positive environmental externality. Essentially, this is a cross-subsidy in which RE is supported in part by conventional generation methods. Unfortunately, tax credits are subject to approval and renewal and are dependent on budget availability, making them unreliable tools for sustained development of RE (Bolinger, 2008; Carley, 2011; Harper et al., 2007; Kahn, 1996). Additionally, tax investors have interests that are not always aligned with the developers. Evidence from India showed that while investors were motivated to build more RE infrastructure, they were not incentivized to ensure continued electricity output (Pillai and Banerjee, 2009; Rajsekhar et al., 1999).

Numerous regulatory policies exist to help developers realize RE projects. At the most basic level, just having a renewable energy policy signals to investors a government’s support and confidence in the technologies. Similarly, pledges to reduce emission level show a long term commitment to sustainable development and environmental awareness. These policies ensure that a minimum standard is met, for example, at least a certain amount of electricity is produced from renewable sources. Below, I discuss two regulatory measures most relevant to this dissertation in detail, particularly for Chapters 2 and 4, the Kyoto Protocol and its accompanying Clean Development Mechanism, and renewable portfolio standards. These regulatory measures often lead to market-based compliance methods, which have been found to be more effective and efficient than tax incentives (Langniss and Wiser, 2003; Palmer et al., 2011).

Kyoto Protocol and Clean Development Mechanism

The Kyoto Protocol is an international treaty between member states of the United Nations Framework Convention on Climate Change, adopted in 1997 and entered into force in 2005. A binding pledge was adopted by several industrialized ("Annex I") nations to reduce or limit greenhouse gas emissions compared to a base-year level, 1990 for most countries, in two commitment periods, 2008 to 2012 and 2013 to 2020. Currently, 37 Annex I countries have binding reduction targets ranging from 0.5 percent to 24 percent by 2020. Notably, the US did not ratify the treaty, and Canada, Japan, New Zealand and Russia either withdrew from the treaty or did not renew their targets for the second commitment period.

The Kyoto Protocol is a cap and trade policy. While emission levels are capped for each country, compliance can be achieved in several ways, in part by using zero- or low-emitting technologies for energy that was previously produced with higher emitting methods, like burning fossil fuels. Since greenhouse gases differ in their impact on the environment, reductions are measured in equivalent tonnes of carbon dioxide (CO_2). Emission reduction is awarded with one certificate per tonne of CO_2, which must be turned in for compliance. For example, if a country was emitting 100 units of CO_2 and had a 20 percent reduction target, it must turn in 20 certificates at the end of the compliance period. Countries that reduce beyond their targets are able to sell their credits through intergovernmental emissions trading to countries unable to meet their targets. The European Union Emission Trading Scheme (EU ETS), for example, facilitates buyers and sellers of carbon credits, intended to reduce emissions in the most cost effective manner.

In addition to its own actions at emission reduction and purchasing credits, an Annex I country can meet its target through flexibility mechanisms built into the Kyoto Protocol, most notably the Clean Development Mechanism (CDM). The CDM allows Annex I countries to invest in a sustainability project in a developing country (host country) that has no binding emission reduction goals. The project "generates" avoided emissions compared to a baseline scenario. In other words, total emissions with the project are less than if the host country were to proceed with business as usual. The majority of CDM projects are new renewable power plants and fuel replacement projects. Projects must apply for approval; registered projects are awarded emission avoidance certificates, also known as Certified Emission Reduction (CER) certificates, for each tonne of avoided CO_2 or its equivalent. CERs can be used by Annex I countries to meet part of their binding commitments. Developing countries benefit since they receive investment in domestic infrastructure, and their ability to achieve economic growth is largely tied to energy supply. In theory, the CDM should encourage bi-lateral development of renewable energy projects in developing countries, in which an industrialized country's investment in a project is repaid in part by CERs. Recently, unilateral projects developed solely by the non-Annex I host country have also emerged. The CERs are sold via various exchanges to a country looking to meet its own binding target, similar to the way Annex I countries trade credits between one another. Even so, the CDM has been one of the primary ways in which developed countries subsidize renewable energy infrastructure in developing countries (Donovan and Nunez, 2012; Hultman et al., 2012; Lewis, 2010).

Renewable portfolio standard

Renewable portfolio standards (RPS), also called renewable purchase obligations (RPO), require a certain amount of electricity to be produced from renewable sources and are used to raise demand for a specific or set of RE technologies. Each unit of electricity produced from renewable sources is associated with a renewable energy certificate (REC), and utilities that purchase electricity to distribute to consumers must be able to produce the required amount of RECs. Some standards apply at the country level, including those for China and Australia, while some others target smaller areas, such as state level programs in the US and India. Additionally, there may be callouts for specific technologies. For example, New Jersey requires at least 5316 GWh of electricity to be produced by solar technologies within the state.

The rules and regulations of each RPS vary widely even within the same country. The differences between US programs, for example, including compliance percentages, existence of technology carve-outs, and even the definition of “renewable” (Carley, 2009; Davies, 2010; Langniss and Wiser, 2003). In some programs, the electricity and the RECs are treated separately. In these cases, utilities purchase power to serve their customers and RECs to comply with regulations, sometimes from different sources. Markets similar to the ones for carbon credits facilitate transactions between RE producers and utilities. Noncompliance leads to fines, or alternative compliance payments (ACP), although inadequate enforcement has been observed in some programs.

DISSERTATION THEME AND FORMAT

While great strides have been made to shift towards a sustainable energy economy, continued support is necessary as renewable energy depends on a high level of regulatory drivers as compared to other industries (Burer and Wustenhagan, 2009). I extend previous research on how energy policy and incentives impact RE development, their weaknesses and unintended consequences, the certain financing methods they favor and the ways in which they can improve. There is tension in the existing literature as to which policy actions work best. Evidence from some empirical studies suggest that tax incentives were the primary policy motivator for increased investment in wind power projects (Bird et al., 2005; Pillai and Banerjee, 2009; Rajsekhar et al., 1999). Other researchers have found, however, that regulatory measures were more effective (Davies, 2010; Nogee et al., 2007; Palmer et al., 2011). While continued analysis and improvement of energy policy will aid renewable energy growth, the conflicting studies indicate that perhaps there is no “one size fits all” policy solution. In fact, results from a survey study by Luthi and Prassler (2011) showed investor preference for policy measures varies not only with the existing policy environment, but is also dependent on the national investment culture and other organizational and behavioral factors. A narrower focus is necessary to address the needs of different countries.

This dissertation is motivated by the conclusion that “energy policy cannot be formulated in isolation from…social and other objectives,” and countries require different approaches for RE growth based on their unique landscape of existing policies and goals for sustainability

(Mahadevan and Asafu-Adjaye, 2007, p. 2488). The research presented here follows the three paper format. The overarching research question of "how can policy be leveraged to increase renewable energy development?" and the subtopics explored are presented in Figure 1.

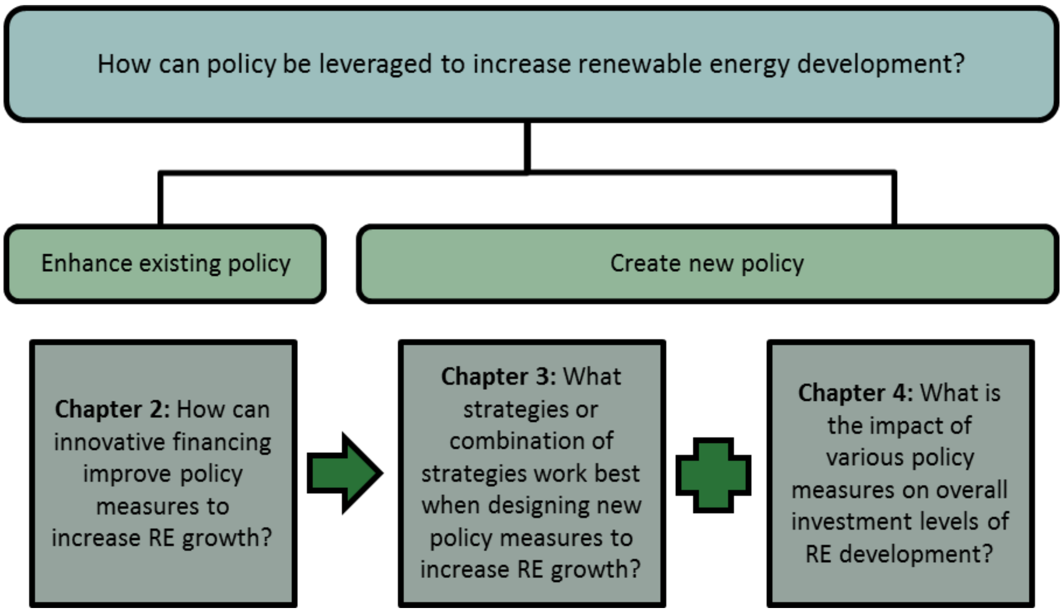

Figure 1. Overall research question and subtopics explored.

Chapter 2 presents the first paper, which introduces a new financing instrument for RE projects to enhance regulatory policy such as emission limits and minimum RE production requirements in countries with markets to support credit trading. I begin by analyzing federal and state level incentives used in the US to promote wind power development and the most prevalent financing structures that have emerged as a result. Focusing narrowly on their weaknesses, I propose the "carbon revenue bond" as a financial instrument which can be used to complement REC and carbon markets where one exists. The bond securitizes future revenue to help address the high capital costs of RE. I present a way to price the bond using stochastic methods and demonstrate the impact of the bond in three international markets: the European Union carbon market, the Australian REC market, and the New Jersey Solar REC (SREC) market.

Chapter 3 begins to address countries that are newer entrants into the renewable energy industry, namely developing countries, and are still seeking to create efficient policy measures. I do so by examining why some policy measures are more effective than others at encouraging wind power diffusion in India. The segmented nature of the Indian energy sector with a high level of state autonomy provides for interesting comparisons across different states. I use a diffusion of innovation lens to analyze strategies used by organizations to promote diffusion. Building on past literature, I develop the strategic structure matrix as a novel framework to improve analysis on how organizations impact diffusion. The explanatory value of the matrix is established by examining the different incentives offered in five states—Tamil Nadu, Gujarat, Maharashtra, Karnataka and Andhra Pradesh—and the resulting patterns of diffusion.

Building on the findings of Chapter 3 which qualitatively explain why some policies are more effective than others, Chapter 4 provides a method to determine the quantitative impact of a policy on total RE investment. I develop and build an agent-based model to simulate total investment RE infrastructure under different policy scenarios. I use the model to determine the impact of suggested improvements to the CDM on investment in wind power projects in India, Brazil and China. The pricing technique in Chapter 2 is used here to calculate the return on investment and the strategic structure matrix from Chapter 3 is used to complement analysis of the different reactions of India, Brazil and China to the CDM and its improvements. The results provide insight into how future policy can be shaped to achieve maximum impact.

Chapter 5 discusses the overall contributions of this dissertation to designing policy and financial instruments to aid RE development. Chapter 6 suggests future areas of research that would extend and expand on the findings of this dissertation. Lastly, an alphabetical list of references is provided.

Chapter 2

FINANCING RENEWABLE ENERGY INFRASTRUCTURE: FORMULATION, PRICING AND IMPACT OF A CARBON REVENUE BOND[2]

ABSTRACT

Renewable energy systems depend on large financial incentives to compete with conventional generation methods. Market-based incentives, including state-level REC markets and international carbon markets have been proposed as solutions to increase renewable energy investment. In this paper we introduce and formulate a carbon revenue bond, a financing tool to complement environmental credit markets to encourage renewable energy investment. To illustrate its use, we value the bond by predicting future revenue using stochastic processes after analyzing historical price data. Three illustrative examples are presented for renewable energy development in three different markets: Europe, Australia and New Jersey. Our findings reveal that the sale of a carbon revenue bond with a ten year maturity can finance a significant portion of a project's initial cost.

[2] This paper was co-authored with Professor Nicola Chiara and Professor John E. Taylor. It is published in Energy Policy. The citation of the journal paper is as follows:

Tang, A., Chiara, N., Taylor, J.E. 2012. Financing renewable energy infrastructure: formulation, pricing and impact of a carbon revenue bond. Energy Policy 45: 691-703.

INTRODUCTION

Over the next 20 years energy consumption is projected to rise by 50% (Energy Information Administration, 2010a). Meeting these increased demands with energy produced from fossil fuels is unsustainable and detrimental to the environment. Generating energy from renewable sources simultaneously address the dual concerns of rising energy demands and the need to reduce environmental pollution. Yet renewable energy projects are extremely capital-intensive. The amount of revenue collected during operations is small relative to the initial cost, leading to a long payback period. Owners and developers of renewable energy infrastructure turn to outside investors to finance portions of the high initial capital costs.

In this paper, we discuss incentives currently being used to promote renewable energy development, many of which, such as the federal Production Tax Credit (PTC) and state-level Renewable Portfolio Standards (RPS) programs, do not help defray the high initial cost. We then propose a “carbon revenue bond” as a financial instrument which can be used to complement Renewable Energy Credit (REC) and carbon markets where one exists. The bond essentially securitizes future revenue from REC or carbon credit sales to raise initial capital from investors, who are later repaid with those future revenues. We describe a way to price the bond using stochastic processes to predict future credit prices after analysis of historical data. Its use is demonstrated in three illustrative examples during which a hypothetical renewable energy system is developed in three different markets: the European Union carbon market, the Australian REC market, and the New Jersey Solar REC (SREC) market. The results show that a carbon revenue bond can finance a meaningful portion of initial development costs. Quantitative risk analysis is also provided for each example. We conclude with a discussion on the potential impact of the carbon revenue bond on renewable energy development.

RENEWABLE ENERGY IN THE US

Deregulation of electricity markets started in the 1990s at a state level. It had the effect of separating the activity of generation from transmission and distribution, and created a competitive market for electricity generation, or wholesale production. Deregulation allowed the private sector to own, operate and otherwise invest in electricity generation infrastructure, including ones using renewable sources, without having to participate in transmission or distribution activities. However, renewable energy systems can have difficulty competing with less expensive generation techniques, such as a conventional coal-fired plant. The U.S. Energy Information Administration (EIA, 2010b) recently published average levelized costs of new generation sources for plants entering service in 2016. Levelized cost is commonly used as a way to compare costs of different electricity generation types. The calculations take into account the initial capital costs, fuel costs, operations and maintenance costs and any necessary transmission investment. The total project cost is then converted into equal annual payments based on the amount of electricity produced, the project life span and financing costs, with the impact of inflation removed. Figure 2 summarizes the EIA’s findings (EIA, 2010b).

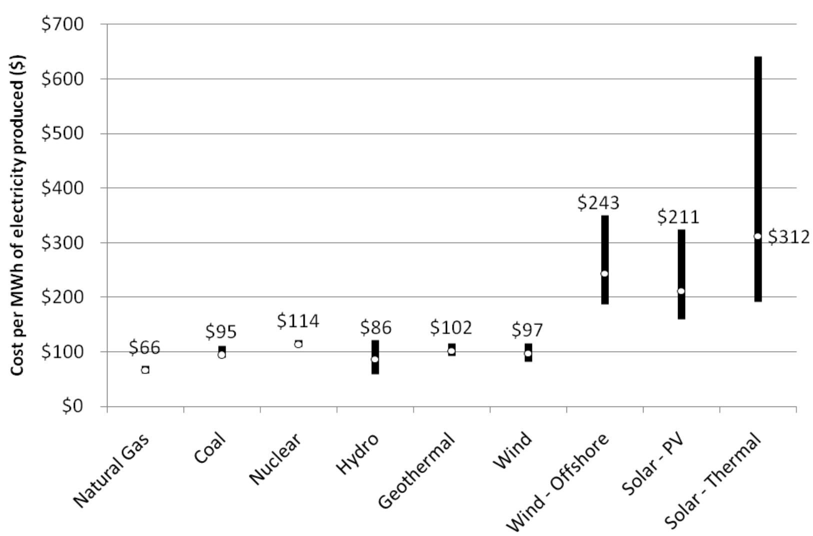

Figure 2. Levelized cost of electricity generation methods.

The black bars indicate the range of estimates and the white circles represent the average costs for each generation type. Offshore wind and both types of solar energy can be over two to three times the cost of coal or natural gas. Even though wind projects developed on land are close to coal costs per MWh of electricity produced, when the amount of electricity produced per year is taken into account, the costs rapidly increase. A 300 MW wind farm, based on a capacity factor of 34% used in EIA's calculations, could produce 893,520 MWh of electricity per year, making the equivalent additional cost almost 1.8 million U.S. dollars per year throughout the 30 year analysis period.

Thus, federal, state and local governments have responded with various policies and financial incentives aimed to "facilitate the diversification of electricity generation mixes, increase renewable energy deployment, reduce state reliance on fossil fuels, help renewable energy sources become cost competitive with conventional energy sources, reduce carbon emissions, or various combinations thereof" (Carley, 2009, p. 3072). In the next section we discuss the strengths and weaknesses of these incentives toward financing renewable energy investment.

Federal level policies and incentives

Issued federally, the Production Tax Credit (PTC) offers privately- or investor- owned renewable energy plants an inflation- adjusted tax credit of 1.5 cents per kWh of electricity generated for the first ten years of its operation. As of early 2012, the credit is priced at 2.2 cents per kWh. Analogously, the Renewable Energy Production Incentive (REPI) provides the same credit to renewable plants owned by utilities, governments or rural co-ops (Menz and Vachon, 2006). Both were instituted as a part of the Energy Policy Act of 1992. The Investment Tax

Credit (ITC) and Treasury grant gives a one-time tax break or grant, respectively, based on the initial amount of project investment during the first year of service (North Carolina Solar Center, 2010). A Treasury grant may cover up to 30% of initial capital costs for certain renewable sources (North Carolina Solar Center, 2010). As a part of the American Recovery and Reinvestment Act of 2009, renewable energy developers can apply to receive a cash payment totaling 30% of eligible project costs in lieu of tax payments, although funds are limited. Additionally, low and no interest loans and bonds are available to help finance qualified projects (North Carolina Solar Center, 2010).

Although current federal incentives promote renewable energy investment, they depend heavily on the political climate and continued legislative support. The PTC, for instance, has been found to be the most effective of the federal incentives (Bird et al., 2005). However, it has expired and been extended numerous times, often with extended lapses, and did not exist for most of 2004. When the credit is extended, it is generally only for one or two years at a time. Additionally, PTCs can only be used by projects that entered service during a year that credit was in place. For example, a wind farm that entered service in 2004 would not be eligible to receive the credit when it was renewed in 2005. Its sister credit, the REPI, is dependent on allotments from the Congressional budget and carries with it large amounts of uncertainty (Bird et al., 2005). The constant threat of disappearing credits makes it extremely difficult to plan financially for the project's lifespan. The initial planning and permitting process may take over two years, by which time the credit may have already expired and construction on the facility not even have begun. Developers that depend on the PTC as a subsidy to make a project financially attractive hesitate to construct new facilities or may abandon renewable energy projects all together. The bust-boom cycle of wind power development in the early 2000s were caused in part by the uncertainty surrounding these credits (Bolinger et al., 2009; Harper et al., 2007). In general, tax incentives have played a secondary role to other policy instruments as promoters of renewable energy development (Carley, 2011).

Another feature of the PTCs ill-suited for renewable energy projects is the timing of the payment. Specifically, renewable projects require greater up-front costs than conventional power plants while having no fuel costs, but the tax incentive is given at the power production stage instead of during initial development (Harper et al., 2007). In the aptly titled article "The production tax credit for wind turbine power plants is an in effective incentive," Kahn (1996) drives the point home, saying "the tax credit…does nothing to bring the capital structure of wind projects more into line with the competing conventional alternatives" (Kahn, 1996, p. 432). In effect, there is no assistance to facilitate the high initial capital investment while the increased revenue stream at the production level occurs when fuel costs are zero. This mismatch has complicated financing for wind projects especially for developers with insufficient need of the full tax benefits (Harper et al., 2007). Innovative financing structures discussed later in the paper have evolved to circumvent the mismatch but have become problematic in their own way after the recession (Harper et. al., 2007).

State level policies and incentives

States have played an increasingly large role in setting their own policies and objectives for renewable energy development (Rabe, 2011). Many of them mirror federal incentives and include tax exemptions/deductions/credits, grants, loans and production incentives, some of which may cover up to 30% of development costs (Menz and Vachon, 2006; North Carolina Solar Center, 2010). Around 40 states have some sort of Renewable Portfolio Standard (RPS) legislation (North Carolina Solar Center, 2010; Davies, 2010), under which utilities are required to purchase a certain percentage of total electricity delivered to the end user from renewable sources. Several studies have evaluated the effectiveness of different state policies on renewable energy development (Langniss and Wiser, 2003; Bird et al., 2005; Menz and Vachon, 2006; Carley, 2009). For a more in-depth review of state energy policy instruments, please see Carley (2011). Combined, these studies suggest that an RPS can effectively promote renewable energy development if designed and implemented well. A positive correlation is found between renewable energy production of a state and the presence of RPS policies in its neighbors, as well as the number of years a state's RPS has been under implementation.

However, these programs vary drastically from state to state. For a more detailed analysis of policy differences, please refer to Wiser et al. (2007). The lack of uniformity between state programs, including differences in compliance percentages, existence of technology carve-outs, and even the definition of "renewable," creates an uneven playing field and a "market distortion" of its true value (Davies, 2010). This implies inefficient development of renewable energy with respect to technology choice and geographical location on a national level. Taken individually, the RPS of some states has been much more successful at increasing renewable energy developments than others. Discrepancies in their effectiveness have been attributed to program designs, where some states may have overly aggressive RPS benchmarks, too many exemptions, or inadequate policy enforcement (Carley, 2009; Langniss and Wiser, 2003).

Furthermore, since revenue from credit sales are not received until after the start of electricity production, these incentives do not help overcome the initial high capital costs associated with renewable energy infrastructure. This is the same problem with the Federal PTCs, suggesting a lack of adequate incentives to aid with the high start-up costs.

Regional policies and incentives

Although proponents of a national RPS believe that it is more economically effective and efficient than an aggregate of fragmented systems (Davies, 2010; Nogee et al., 2007) and studies have evaluated potential efficacy of different national systems (Palmer, 2011), energy policy will likely remain state-centric in the upcoming years (Rabe, 2011). But in the absence of national legislation, leaders of states and regions have formed regional initiatives and voluntary emissions markets. The most developed is the Regional Greenhouse Gas Initiative (RGGI), composed of ten states in the Northeast, which started carbon auctions in 2008 (Rabe, 2011). The Western Climate Initiative (WCI) and Midwestern Greenhouse Gas Reduction Accord (MGGRA), with participation from both US states and Canadian territories, are still deciding on their emission allowance processes (Rabe, 2011). Similarly, there are several international cap-and-trade programs that formed as a result of the Kyoto Protocol, under which many nations pledged to reduce their carbon output. The most mature market is the European Union Emissions Trading Scheme (EU ETS). Again, like the PTC and REC trading in RPS programs, revenue from carbon credit sales are not received until after electricity production and therefore the developer is required to secure initial capital in other ways. In this paper, we refer to both RECs and carbon credits collectively as “environmental credits” which are issued by a central authority and can be traded.

Financing structure for renewable energy in the US

The emergence of PTCs and state-level incentives has led the renewable power industry, more specifically the wind energy industry, to come up with innovative ways to finance its projects that take full advantage of those incentives. A survey done by Bolinger et al. (2009)

identifies six principal financing structures through which most utility-scale wind projects from 1999–2008 have been developed in the United States. The study excludes utility-owned projects which are subject to different tax regulations.

The traditional way to finance a wind project is with a corporate structure. The parent company invests 100% equity into the project and in return receives all of the cash revenue and all of the tax benefits. However, only large developers have been able to take full advantage of the tax benefits, including the PTCs discussed earlier. This has led to the emergence of two types of tax investors: the strategic investor and the institutional investor. Both the strategic and institutional investors are larger entities who contribute equity to the project and are able to fully use the tax benefits, but the strategic investor is seeking an active role in the project and contributes more equity while the institutional investor is a more passive party and contributes less equity. The revenue from electricity sales and REC sales go to the project developer while the PTC and any additional tax savings are received by the investor.

In the back leveraged structure, similar to that of the institutional investor, the developer takes on third party debt to cover his/her share of the equity contribution, while the tax investor contribution remains the same. In the cash leveraged structure, the project company takes on a third party debt to help finance the project, in turn reducing the equity contributions of both the developer and the tax investor. The last structure described by Bolinger is the cash and PTC leveraged structure in which PTCs can also be used to repay project-level debt. This structure has only been used twice in the time period explored.

With the exception of the corporate structure, the other structures depend heavily on outside tax investors for financing. Entities able to take advantage of such considerable tax benefits are large investment and commercial banks and insurance companies and interest in renewable energy projects have decreased since the 2008 economic downturn (Schwabe et al., 2009). Also notable about all six structures is that, while developers and investors alike have separated out the PTC savings as a distinct avoided expense and have even used it to leverage debt, they continue to lump electricity sales and REC sales into a single cash stream. Perhaps this is because RECs do not currently exist in all states, or maybe because some REC markets are relatively new in some states. Whatever the reason, combining electricity and RECs into a single revenue pool from which to pay back debtors or earn returns does not efficiently highlight the differences in their characteristics or adequately mitigate the risk profiles of each asset. Creating two revenue streams allows investors to participate in each market separately and make more managed decisions about their investments and their associated risks. In fact, the very existence of unbundled REC markets suggests a natural separation of electricity and RECs. With more states considering RPS and existing REC markets growing more mature, it is sensible that renewable energy project developers treat these incentives as a distinct and sizable cash flow stream.

In this paper, we develop a novel financing tool that securitizes the future revenue of these credits in the form of a carbon revenue bond. The carbon revenue bond addresses the problem of current financing structures under which developers do not receive revenue from the sale of environmental credits until after electricity production starts, a situation that does nothing to help overcome the high start-up costs. With a carbon revenue bond, a renewable energy developer sells a bond to an interested investor who is repaid with revenue from the future sale of environmental credits. The bond raises money at the project development stage, thus providing the developer with funds up-font to defray the significant capital costs of renewable infrastructure. Moreover, it does not require investors to have heavy tax obligations, a problem with PTCs, therefore expanding the pool of available candidates. The following section will provide a brief background on revenue bonds, describe the structure of a carbon revenue bond and demonstrate its use.

CARBON REVENUE BOND

Background on revenue bonds

Local governments have been issuing municipality bonds for decades. They are generally used to finance public infrastructure needs such as roads, schools, power and water facilities, hospitals, public housing, etc. The bonds can be either general obligation, in which the repayment is secured by the issuer's ability to tax, or a revenue bond, where the investor is repaid by proceeds from a pool of projects and its ability to generate revenue. In the case of a project revenue bond, the bond purchaser chooses to invest in a specific project, for example a bridge, and interest and principle repayments are secured only with future revenue generated by user fees such as tolls. If the project does not perform as expected and revenues are lower than projected, the investor has no recourse over the issuer's other assets or profitable projects. A notable example of this is the original Tacoma Narrows Bridge, financed partly using project revenue bonds, which collapsed shortly after its opening in 1940. Had it not been for insurance, the bond holders would have lost all of their investment (Fordham, 1942).

Investors are drawn to revenue bonds because of their relatively low-risk profile and tax-exempt status on interest earnings. As a result, the rate of return is usually lower than other market investments. In order to increase the credibility of a revenue- backed bond, rigorous revenue forecasts, sensitivity tests and some form of risk analysis is usually required. Oftentimes additional institutional entities are involved, including a bond issuing agency and a credit rating agency (AASHTO, 2011).

The emergence of public–private-partnerships in infrastructure has led to the creation of private activity bonds. A special type of revenue bond, the private activity bond is issued by a private enterprise tasked with developing public infrastructure. Certain projects categories—detailed in the Internal Revenue Code—qualify for tax exempt status.[3] One of them is the new I-495 Capital Beltway HOT Lanes currently under construction in Fairfax Country, Virginia. Out of a total cost of US$2 billion, US$586 million (29.3%) is being financed using private activity bonds backed by toll revenue, also referred to as toll revenue bonds (AASHTO, 2011). Sometimes smaller projects can be financed entirely by these bonds. For the addition of express toll lanes to the heavily congested SR91 highway in Orange County, California, the project company was able to finance the $135 million project using long-term tax-exempt toll revenue bonds (Poole and Orski, 2003). The new lanes are generating sufficient revenue to cover the debt service on the bonds, as well as all operations and maintenance costs (Poole and Orski, 2003).

This subset of bonds is applicable to private sector players who are seeking financing to develop renewable energy assets. There can be two revenue streams for renewable energy projects. The first is the sale of electricity, which is common across all generation assets regardless of source. The second comes from the sale of environmental credits if the project is developed in a location in which a market for them exists. In short, the positive externality of the low- or no-carbon nature of renewable energy systems becomes monetized in these credits, and proceeds from the sale of credits are an *additional* revenue stream to which developers of non-renewable energy do not have access. By securitizing this particular revenue stream in the same

[3] The authors are not well versed in US tax law. Practitioners should always consult tax code before making any assumptions about the tax-exempt status of any private activity bond.

fashion as that of toll revenues, renewable energy developers can sell bonds to finance a project. It should be noted here that these bonds securitize only revenue from the environmental credits and not electricity sales. Creating two revenue streams allows investors to participate in each market separately and make more managed decisions about their investments and their associated risks. Carbon revenue bonds are able to improve upon the good intentions of carbon credits and RECs by not only awarding renewable energy producers a production subsidy, but doing so at the start of the project to overcome high start-up costs. Additionally, like all other project revenue bonds, the carbon revenue bond also protects a developer’s established and future projects from exposure to the risks of the current one. It also protects a developer’s earnings from electricity sales since the two revenue streams are no longer lumped into one.

Structure of carbon revenue bond

Initially, the owner sells and issues the bond to an investor who pays an initial amount *x*. How and when the investor is repaid is commonly referred to as the structure of the bond. As the seller of a revenue bond, there are two components to consider: the asset cash flow, which represents revenue received, and the liabilities cash flow, which represents payments to the buyer of the bond. For simplicity, we will set up the carbon revenue bond as a pass-through bond, so that the asset cash flow mirrors the liabilities cash flow. In other words, whenever the seller of the bond receives revenue from the sale of environmental credits, he or she “passes-through” that revenue directly to the buyer. The examples in this paper use a bond maturity of 10 years. Other types of bond structures, including different bond maturities, bullet bonds and those similar to an annuity are discussed later in the paper.

After paying the initial amount *x*, a carbon revenue bond entitles the investor to collect repayment backed by the revenue from the sale of environmental credits every year for *t* years. The time, *t*, until full repayment is commonly referred to as the bond maturity. We use c_i to denote revenue received from environmental credit sales in year *i*, which will differ year to year based on fluctuating prices in the future. Figure 3 depicts a cash flow diagram for a buyer of the bond.

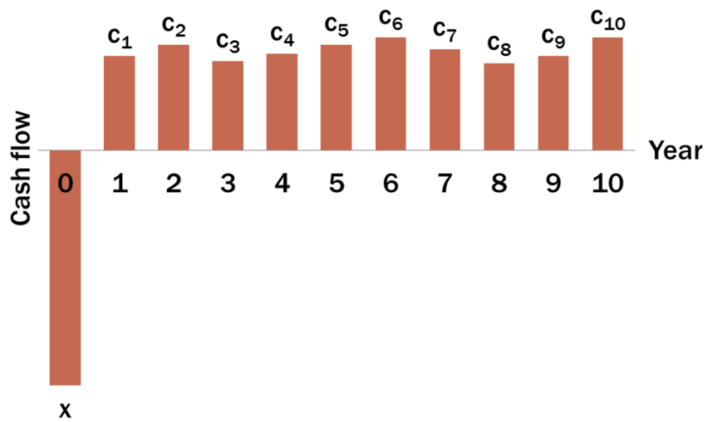

Figure 3. Cash flow diagram for buyer of a carbon revenue bond.

To make the bond a fair investment, the initial investment should equal the sum of the repayment amounts given an appropriate interest rate, *r*, with each c_i properly discounted. Future revenue received from the sale of the credits can be predicted, and the initial price of the bond, *x*, is calculated as follows:

$$x = \sum_{i=1}^{t} \frac{c_i}{(1+r)^i}$$

The equation states that the initial investment is equal to the sum of the discounted value of all future repayment amounts, given a rate of return, *r*. It is critical that environmental credit prices are carefully forecasted for the length of the bond. Grossly inaccurate predictions can lead to unfairly high or low returns for the investor. Therefore, it is important to choose a pricing technique that can appropriately represent future behavior of credit prices. In the following section, we present a way to model future credit prices using stochastic processes, which are commonly used to model other assets. Other models and the inherent risks associated with the uncertainty of future prices are discussed later in the paper.

Modeling of future environmental credit prices

The choice of which model to use to predict future prices is not an easy one. For this paper we chose to use stochastic models, in which the change in price follows a random process subject to a probability distribution. We believe they contain many advantages relative to deterministic models and those that require estimation of other variables. First, environmental credits can be treated as tradable assets or commodities like stocks and steel, and the movement of prices of tradable assets is frequently modeled using stochastic processes (Schwartz, 1997). A large number of processes, including some of the ones used in this paper, have been developed or augmented specifically for use in modeling financial assets. Second, simulating prices using a stochastic process allows developers to quantifiably evaluate the risk of the bond because it provides a range and distribution of projected prices, something deterministic models cannot do. That is, simulation results produce a mean number for the value of the bond, but also a distribution around that mean, so that the probability of loss can be calculated (for example, “there is a 12% chance that losses will be incurred by selling the bond”). Lastly, the data used to calibrate the stochastic models are real, historical prices. Input-output models use predicted values such as global temperature increase, or assign a numerical value to a non-numerical property, for instance, willingness to use clean energy. These models build predictions on top of predictions and can be limiting in their application. To illustrate the use of stochastic processes as a modeling tool, we follow Brigo and colleagues' approach (2009) of simulating future asset prices from several stochastic process and then comparing the results to historical asset prices to determine the best fitting process. Due to space constraints and the fact that this is only for illustrative purposes, only three processes are tested. The following subsections discuss the stochastic models we use: geometric Brownian motion, the NGARCH model, and the Jumps Diffusion model. A summary of the three processes can be found in Table 1. We then provide three illustrative examples on how to price a carbon revenue bond based on historical data from three different credits around the world: European Union Allowances for carbon emissions, Australian RECs and New Jersey SRECs.

Table 1. Description of stochastic processes used.

	Description	*Effect on Results*
Geometric Brownian Motion	Fundamental random process. The increase or decrease in prices for each incremental time step comes from a normal distribution with a mean and standard deviation that remains constant throughout the simulation.	Changes in daily prices will follow a normal distribution centered around a constant mean and standard deviation.
NGARCH	Process that allows volatility to change with time. Instead of staying constant throughout the entire simulation, the volatility changes based on the long run average, the standard deviation from the previous time step, and the direction of price movement with a decrease in price leading to higher volatility in the next time step.	The change in volatility over time generally creates larger magnitude of price fluctuations for each time step. Fatter tails will be observed when looking at the histogram of daily returns over time.
Jumps Diffusion	Process that allows price jumps on top of movement created by GBM. The arrival of price jumps is categorized by a Poisson process which is independent of the GBM random process.	Price spikes can be observed from time to time on top of the daily changes based on GBM. This again creates fatter tails in the histogram of returns over time.

Geometric Brownian motion

Geometric Brownian motion (GBM) is a fundamental random stochastic process for modeling asset price over time, and is represented by the following stochastic differential equation (SDE):

$$dS_t = \mu S_t dt + \sigma S_t dW_t$$

where S_t = asset price,
dS_t = incremental change in asset price,
μ = percentage drift,
σ = percentage volatility (standard deviation of the drift),
and dW_t = Wiener process, also known as standard Brownian motion, a process characterized by normally distributed independent identical distributed (IID) increments with a mean of 0 and variance equal to the time step, dt.

GBM is a Markov Process, which means it is "memoryless" in the sense that only the current price is necessary to predict future prices, and past data does not factor into the model. In discrete form, it reduces to

$$S(t_{i+1}) = S(t_i)\exp\left(\left[\mu - \frac{1}{2}\sigma^2\right](t_{i+1} - t_i) + \sigma\sqrt{t_{i+1} - t_i}\,Z_{i+1}\right)$$

where $Z_1, Z_2, \ldots Z_n$ are independent random numbers generated from the standard normal distribution (mean of 0 and standard deviation of 1). As evident from the equation, all that is necessary to predict the price in the next time step is the current price, the drift, μ, and the volatility, σ, which can be calibrated from historical data using maximum likelihood estimation. Essentially, what is simulated at each time step is the amount of asset returns. Together with information on the price from the previous time step, the price for the next time step is calculated.

There are several limitations to geometric Brown motion. First, it assumes the randomness (the Wiener process) in generating asset returns is characterized by a standard normal distribution. Additionally, it does not capture mean reverting properties and also assumes constant volatility. Many asset prices exhibit behaviors that do not fit neatly into a standard normal distribution and many models have subsequently been developed to capture these intricacies. Next we explore processes that take into account some of the weaknesses of GBM.

NGARCH model

Generalized Autoregressive Conditional Heteroscedasticity (GARCH) models allow volatility to change with time and past information (Bollerslev, 1986). The GARCH(1,1)[4] model is represented by the following equation, where the volatility term, σ, is a function of t:

$$dS(t_i) = \mu S(t_i)dt + \sigma(t_i)S(t_i)dW(t_i)$$

with $$(\sigma(t_i))^2 = \omega\bar{\sigma}^2 + \alpha\sigma(t_{i-1})^2 + \beta(\varepsilon(t_{i-1}))^2$$

and $$\varepsilon(t_i)^2 = (\sigma(t_i)dW(t_i))^2.$$

The variance is a linear combination of three weighted parts: the average long run variance rate, the volatility from one time step before, and an additional random component. Therefore σ^2 is assumed to be a stochastic process by itself. The weights must add up to 1, subject to the constraint $\omega + \alpha + \beta = 1$. The non-linear GARCH (NGARCH) model (Engle and Ng, 1993) is an extension of the GARCH model that follows the assumption that ‘‘good news’’ or positive returns decrease volatility and stabilize prices while ‘‘bad news’’ or negative returns do the opposite. The equation for the NGARCH model is

$$dS(t_i) = \mu S(t_i)dt + \sigma S(t_i)dW(t_i)$$

with $$(\sigma(t_i))^2 = \omega + \alpha\sigma(t_{i-1})^2 + \beta(\varepsilon(t_{i-1}) - \gamma\sigma(t_{i-1}))^2$$

and $$(\varepsilon(t_i))^2 = (\sigma(t_i)dW(t_i))^2.$$

The NGARCH model has an extra parameter, gamma, which is always positive, that reduces the impact of “good news” and increases the impact of “bad news.” These conditional

---

[4] In a GARCH(p,q) model, p and q represent the lag time and number of terms used, respectively, in producing the next data point. The GARCH(1,1) model uses 1 data point 1 day ago.

changes in volatility produce fatter tails in the distribution of simulated results instead of normally distributed as in the case with GBM.

Jumps Diffusion model

The Jumps Diffusion model (GBM with Jumps) is another way to capture the fat-tailed distribution of asset returns by introducing compound Poisson jumps to model the idiosyncratic shocks experienced by asset prices. This model was first used to price stock options (Merton, 1976). The stochastic differential equation is

$$dS_t = \mu S_t dt + \sigma S_t dW_t + S_t dJ_t$$

which is the GBM equation plus the univariate jump process, $dJ(t) = (Y_{N(t)} - 1)dN(t)$.

The arrival of the jumps are determined by the Poisson process N, a discrete probability distribution that gives the probability, λ, that an event will happen in a given time period. Thus the expected number of jumps occurring in time t will be λt. The size of each jump is determined by yet another random variable, Y, a log-normal distribution with mean μ_Y and standard deviation σ_Y. The Brownian motion W, the Poisson process N, and the size of the jumps Y are all independent from one another. The most straightforward way to simulate prices is by modeling the log-returns at time t, defined as

$$\Delta \log(S(t)) = \mu^* \Delta t + \sigma\sqrt{\Delta t} + \Delta J_t^*$$

subject to $$\mu^* = \mu + \lambda\mu_Y - \frac{1}{2}\sigma^2$$

and $$J_t^* = \sum_{j=1}^{n_t} \log(Y_j) - \lambda \Delta t \mu_Y \ .$$

The returns can then be used to compute the price, S, for each time step.

ILLUSTRATIVE EXAMPLES

In this section we provide three illustrative examples to illustrate the potential impact of the carbon revenue bond on financing hypothetical yet realistic projects in three different markets: Europe, Australia and New Jersey. The frequency of and avenue through which environmental credits are traded vary from location to location. In Europe, the credits are traded at high volumes daily on an exchange and data is easily obtainable. In Australia, credits are mainly traded through brokers in over-the-counter transactions and data is not available for all days. In New Jersey, monthly averages of credit prices are used due to low trade volume and the state also has an alternative compliance payment, which has the same effect as a price cap. The three examples chosen illustrate a range of trading systems and a way to price the carbon revenue bond in each case, demonstrating wide applicability of the bond.

European Union Allowances

European Union Allowances (EUAs) are carbon credits used by European Union member states as a part of the European Union Emissions Trading Scheme (EU ETS) to lower emission levels. We start with EUAs because the EU ETS is the largest and longest established trading scheme with high volumes of credits being traded. Our data consists of historical spot prices, also known as next day futures, of EUAs traded on the European Climate Exchange from September 1, 2009 through August 31, 2010, consisting of 255 data points. It should be noted that information from any over-the-counter trades occurring during this time period is not included. Figure 4 includes graphs of asset price, asset log return, and their respective histograms.

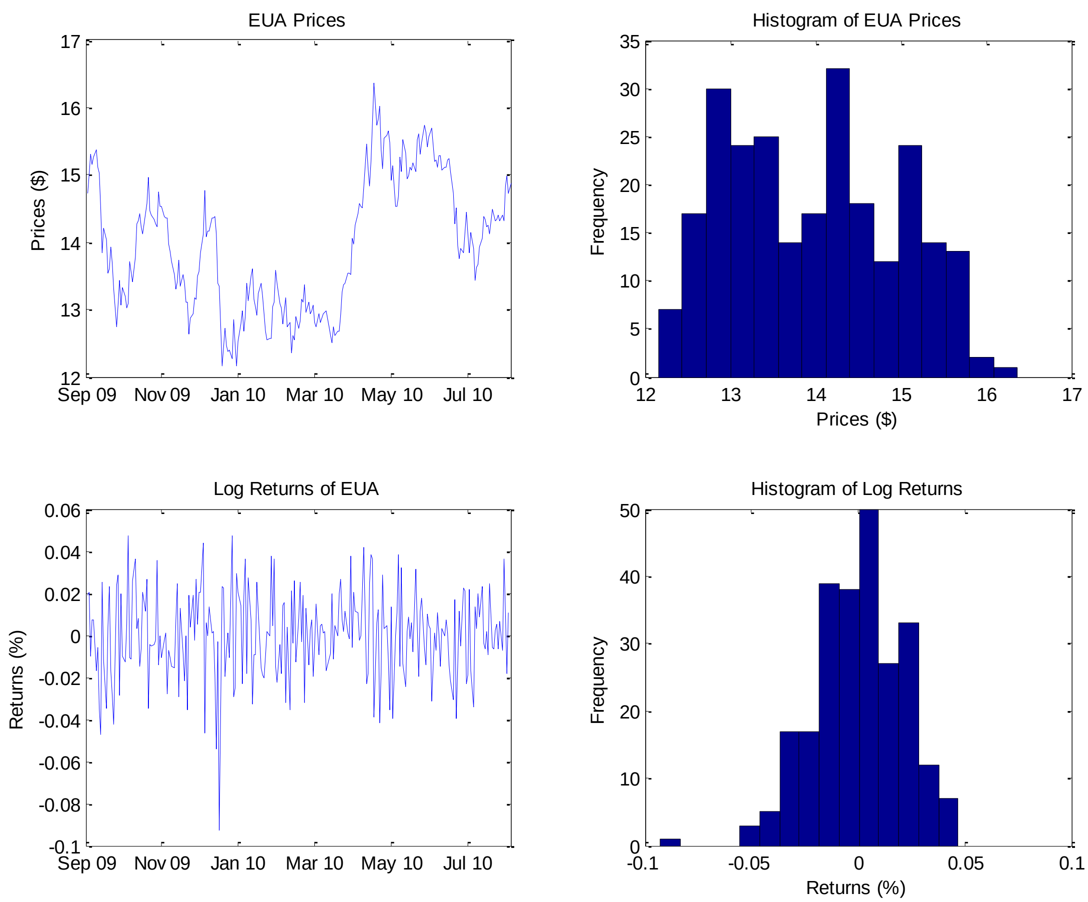

Figure 4. Time series and histograms of EUA prices and log returns.

Log returns are often used instead of asset prices to normalize data, where an increase in price during a time step correlates to positive returns, and vice versa. Using log returns allows comparison of different assets as well as of the same asset over different periods of time. Log returns also exhibit bell-shaped features in their distributions, as can be seen in the bottom right graph in Figure 4, and the stochastic process we used takes random pulls from the distribution of that process to generate log returns for the next time step in order to calculate the asset price. Following Brigo et al. (2009), we used the returns level data to calibrate the parameters for each of the stochastic processes (GBM, NGARCH and Jumps Diffusion) using maximum likelihood estimation (MLE). In general, MLE selects parameter values which produce the distribution from which the sample data was most likely taken. This is akin to fitting a set of a data to a hypothesized distribution by changing its variance, skewness, kurotosis, and any other parameters that determine the shape of the distribution. Table 2 summarizes the calibrated parameters, as well as the *p*-values for each model. The *p*-values are calculated using a two-sample Kolmogorov-Smirnov test which tests the null hypothesis that the historical returns and simulated returns come from the same distribution. Using the commonly accepted 5% significance level, *p*-values below 0.05 cause us to reject the null hypothesis. In other words, if the *p*-value is less than 0.05 for a particular stochastic process, we can say that the historical values and the values simulated using that process does not come from the same distribution, and that the process is not a good representation of how asset prices behave. Higher *p*-values suggest a greater likelihood that the two samples are from the same distribution. These values, along with quantile-quantile plots discussed below, will enable us to determine which process is most appropriate for EUAs during the time period examined. Finally, using the historically calibrated parameters, we simulated 10,000 paths for each process for a time period of 10 years (2500 time steps), starting at a price of €15.20.

Goodness of fit to a particular process can be assessed using a quantile–quantile plot (QQ plot) (Brigo et al., 2009). The y-axis plots the quantiles of the historical EUA returns and the x-axis plots the quantiles of the distribution of the simulated returns for a particular process. If it is a good fit to the historical data, then the QQ-plot approximates a straight line. However, if the plot diverges from a straight line, then the stochastic process fails to capture all of the properties of the asset prices from that time period. Figure 5 contains the QQ plots for the processes tested.

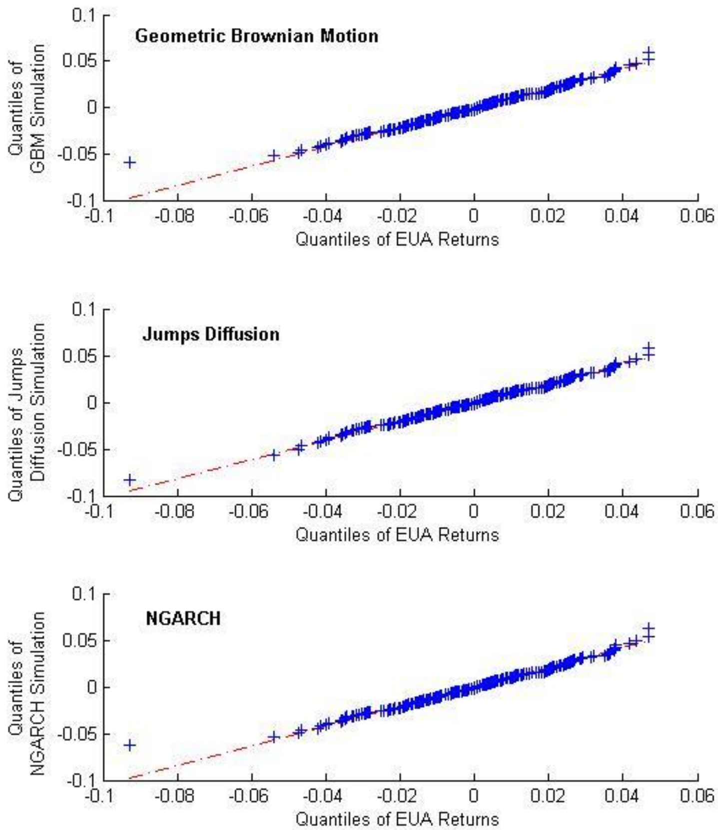

Figure 5. QQ plots of EUA returns versus simulated returns.

In evaluating the QQ plots, it is important to concentrate on the portion of the distribution critical to the analysis being performed. Referring back to the structure of the carbon revenue bond discussed earlier in the paper, the risk to the renewable energy developer is that the future revenues from RECs, carbon credits, or other financial incentives are inadequate to cover the debt obligation to the investor (the original bond purchaser). As a result, the lower left quadrant of the graph should be studied in order to find a model that most accurately predicts potential downside risks. We see that all models are good estimators of EUAs given data from September 1, 2009 to August 31, 2010 with the exception of one data point. This corresponds to the outlier in the returns of historical prices which is visible on the histogram of returns data on the lower right graph of Figure 4. However, the Jumps Diffusion simulation places this point closest to the line. Referencing Table 2, we observe that the *p*-values are all above 0.05, with the Jumps Diffusion model giving the highest *p*-value of 0.70864, providing quantitative support for our visual inspection. Weighing these factors, we can conclude that, out of the three models tested, the Jumps Diffusion process best approximates EUA prices given data from the time period examined.

Now we use the simulations from the Jumps Diffusion process to price a carbon revenue bond to finance a hypothetical 200MW wind power plant located in Europe. The European Wind Energy Association provides a rough estimate of the average cost at €1000 per kW of capacity (Morthorst, 2004), making the total cost of development for our wind plant €200 million.

The first step is to estimate the amount electricity produced and the amount of potential carbon savings for which the developer would receive credits. Assuming an average capacity factor of 30% each year,[5] the average amount of electricity produced by the wind farm is 525,600MWh per year. The Carbon Trust recommends a conversion factor of 0.43t of CO2 saved per MWh of electricity produced for all renewable technologies, providing the developer with 226,008 credits yearly. We assume that the credits are sold at the end of each year, although developers are free to choose their own trading strategy. For each path of the Jumps Diffusion simulation, we multiply each year-end value by the number of credits to calculate the expected revenue per year. Finally, we take the present value of each path assuming a discount rate of 7% to determine the value of the carbon revenue bond.

In fact, what we end up with is a bond price for each path, in our case 10,000 values. Each of these represents one possible scenario under the assumption that the price of EUAs follows a Jumps Diffusion model. We take the median value of €30.2 million as the price of our

[5] Typical capacity factors for wind are between 20 and 40%.

carbon revenue bond for this particular wind project. This securitized cash stream can be sold to one party or broken up for sale to multiple parties, each one having a claim to a percentage of future EUA revenues. In this case, the bond or bonds are able to finance 15.1% of initial project costs. The histogram of simulated total bond values can be found on the left in Figure 6.

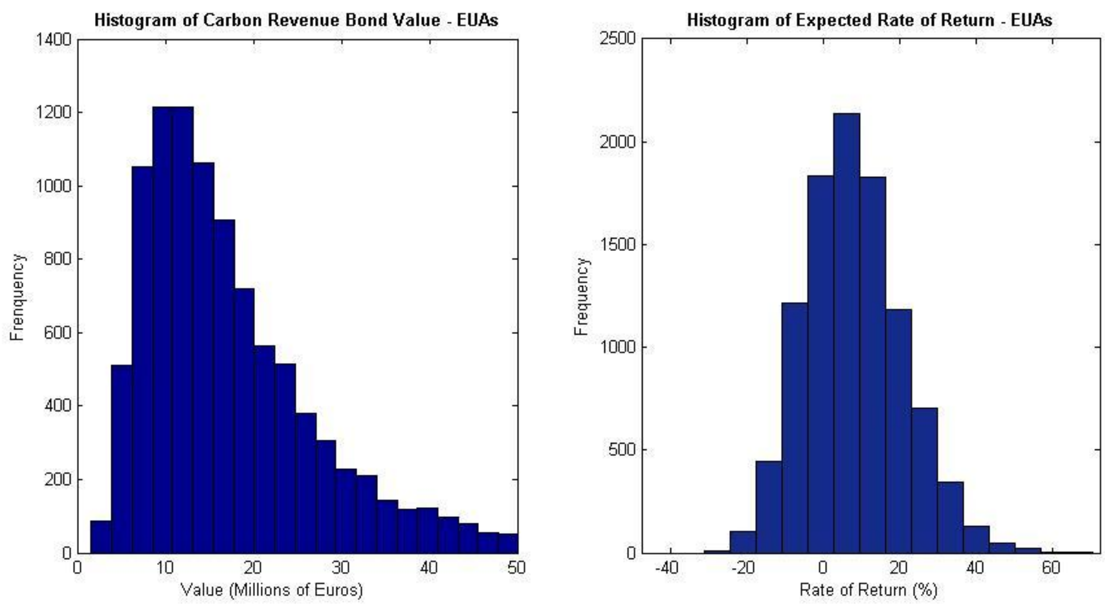

Figure 6. Histogram of bond value and histogram of expected return for EUAs.

As mentioned before, an advantage of stochastic modeling is the ability to not only determine a bond value, but also perform quantitative risk analysis. The histogram provides the probability distribution of the bond value. The upper and lower quartiles have also been calculated, showing that there is a 25% chance the future revenue will be less €20 million and a 25% chance that it will be more than €46.2 million. Most of the time, investors are concerned with their rate of return given the initial investment amount. Using the median bond value, we calculated the internal rate of return (IRR) for each simulated path, as well as the quartiles. We are also able to quantify the risk of losses (negative returns) by finding the probability that the

IRR is less than zero. In this example, the risk is very high at 28.59%. Many investors may walk away from this investment or ask for a higher return to compensate for the additional risk. Methods of risk mitigation are discussed later. The histogram of all IRR values is presented on the right in Figure 6. Details are also provided in Table 3.

Australian RECs

Australia has implemented the use of RECs to help meet the country's renewable energy target.[6] Unlike the EUAs, Australian RECs are not traded daily on an exchange but rather only through over-the-counter transactions. We use data collected by Local Power based on information they have received over the last few years from various brokers. The time period we analyze ranges from January 4th 2010 to December 22nd 2010. Since information is provided only from certain brokers, we do not have recorded trades for everyday during the analysis period and spline interpolation is used to fill in the gaps. Figure 7 includes graphs of asset price after interpolation, asset returns, and their respective histograms.

[6] Starting January 1, 2011, the Renewable Energy Target (RET) was divided into Large-scale Renewable Energy Targets (LRET) and the Small-scale Renewable Energy Scheme (SRES) with qualifying technologies using Small-scale Technology Certificates (STCs) and Large-scale Generation Certificates (LGCs), respectively.

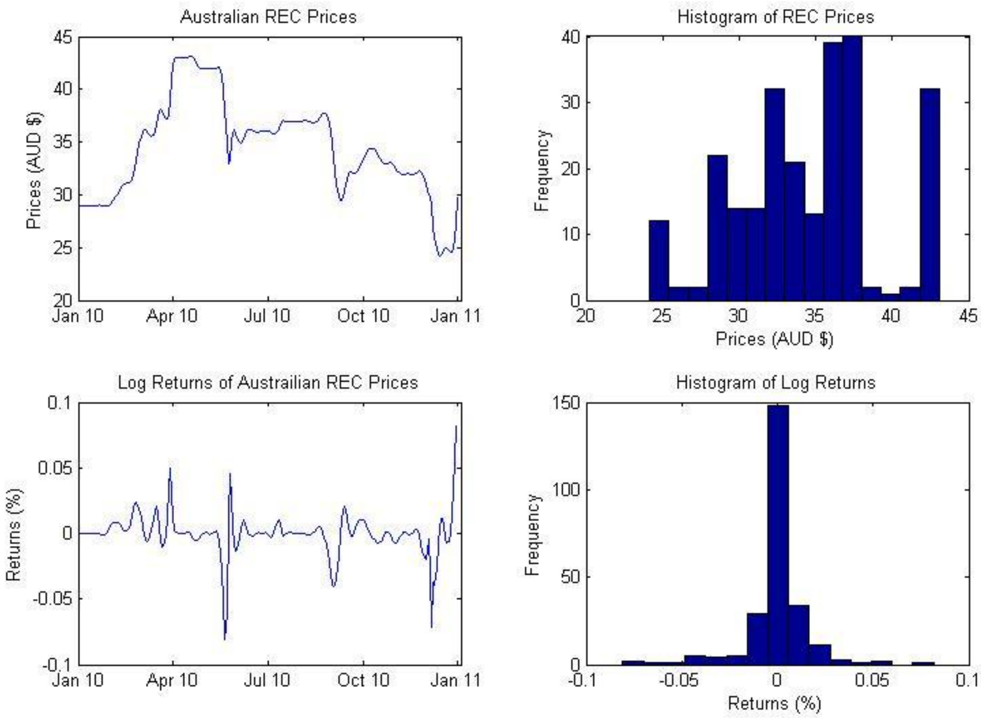

Figure 7. Time series and histograms of Australian REC prices and log returns.

We follow the same process used above to calibrate parameters for the stochastic processes, simulate future prices and determine the best fitting process using QQ plots and the *p*-value from a two-sample Kolmogorov-Smirnov test. The results are detailed in Figure 8 and Table 2. The Jumps Diffusion model appears to have the best fit in the QQ plot, which is supported by the *p*-value of just over 0.05. Histograms of the historical returns and simulated returns shown in Figure 9 are provided for this example as additional validation for the choice of the Jumps Diffusion model over the other two tested.

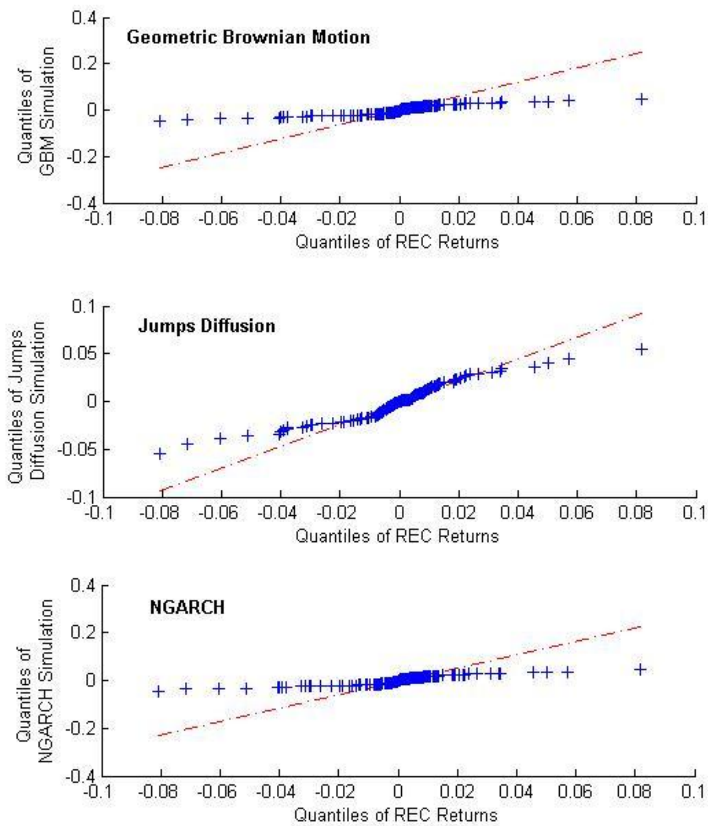

Figure 8. QQ plots of Australian REC returns versus simulated returns.

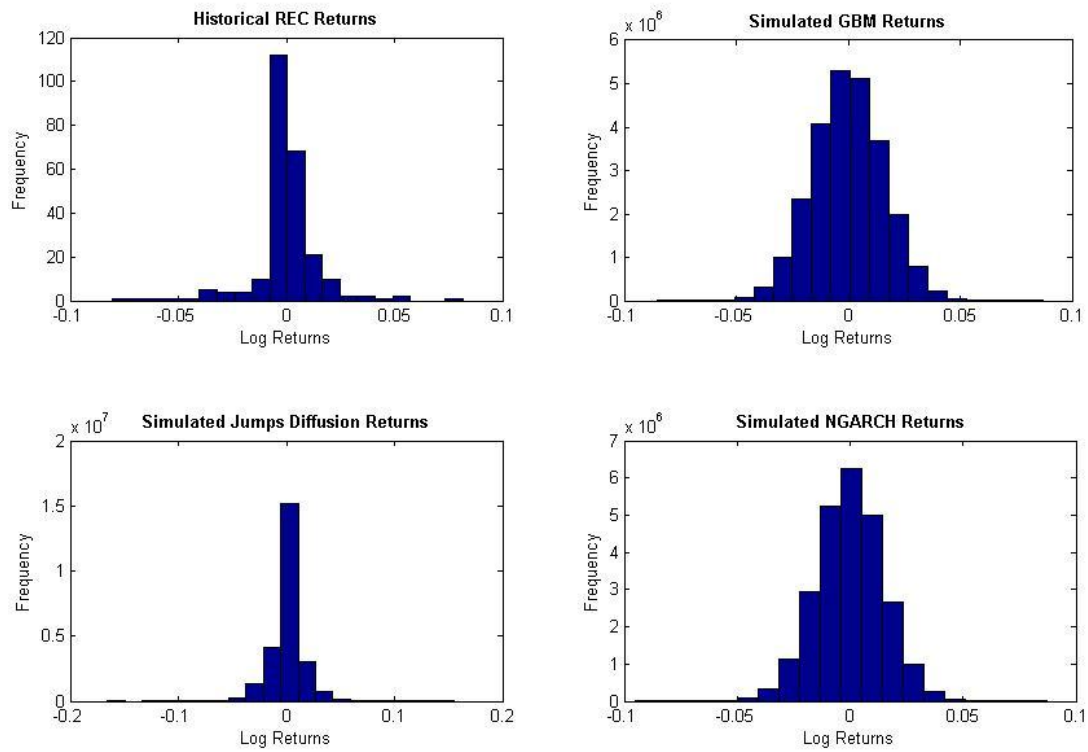

Figure 9. Histogram of historical and simulated Australian REC prices.

Again, we use a 200MW hypothetical wind farm and estimate that the project will cost AU$ 350 based on a similarly sized project currently being developed. We use the simulations from the Jumps Diffusion process to price a carbon revenue bond for Australian RECs following the same methodology as before. However, this time the amount of electricity generated translates directly into the number of RECs received. A 200 MW wind farm, therefore, produces 525,600MWh of electricity yearly based on a 30% capacity factor and is awarded 525,600 RECs per year. The histogram of simulated revenue bond prices is shown in Figure 10. On average, the bond can contribute AU$ 127 million (36.3%) to finance capital costs. Analysis of IRR based on the median bond value places the risk of loss at 20.19% and details of risk analysis can be found in Table 3.

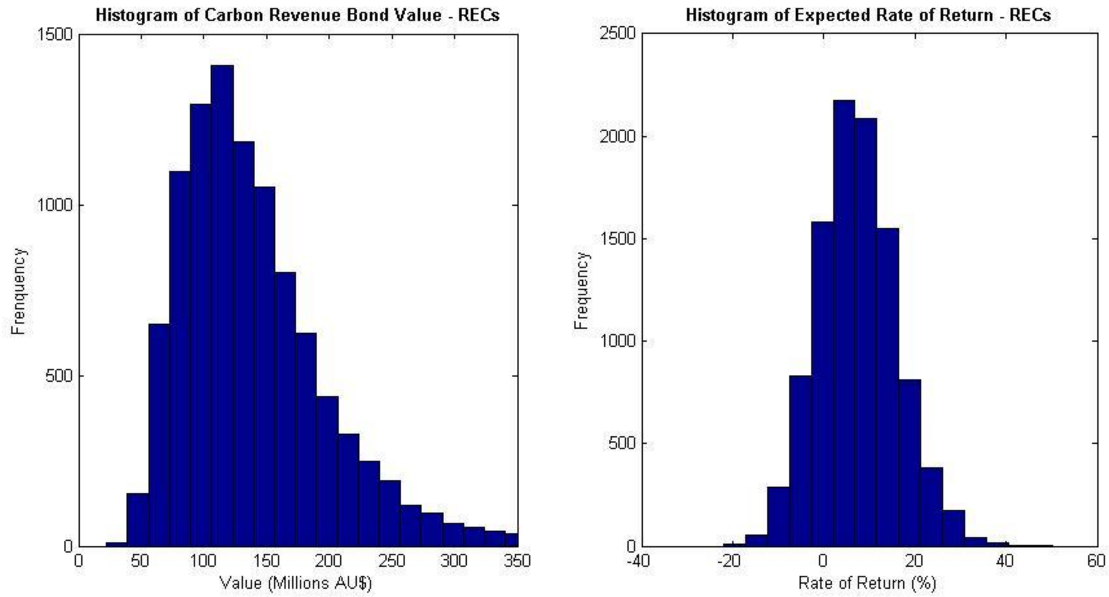

Figure 10. Histogram of bond value and histogram of expected return for Australian RECs.

New Jersey SRECs

The RPS in New Jersey has a specific solar carve-out, requiring that at least 5316 GWh of electricity sold by suppliers/providers to retail customers is sourced from solar technologies within the state. To facilitate this goal, solar RECs (SRECs) are award to energy producers who subsequently sell them to electricity suppliers in an unbundled SREC market.

Similar to the Australian RECs, there are no exchanges on which the credits are traded so over-the-counter trades facilitate all transactions. The market is relatively small compared to our previous two examples because of geographical boundaries. Thus, trade volumes are low and do not happen daily. The data we used comes from the state of New Jersey Clean Energy Program website and consists of monthly averages from December 2008 to September 2011 calculated based on prices reported by registered SREC account holders. With only 34 data points, the calibration of the stochastic models will not be as rigorous as the previous two examples and the results should be analyzed with that in mind. Additionally, since we only have monthly data, it is imprudent to interpolate to daily prices. Therefore we evaluate prices changes on a monthly basis, using 120 time steps to cover a ten year period.

To keep the market in check, New Jersey has implemented an Alternative Compliance Payment (ACP) which electricity suppliers must pay if they do not have enough SRECs. The ACP was set at $711 in 2009 and declines yearly according to a set schedule until it reaches $594 in 2016. Rational electricity providers will not purchase an SREC with a price higher than the ACP since it will be in their best interest to just pay the fine. Therefore when we simulate future SREC prices, we also cap them at the APC. The QQ plots are contained in Figure 11 and the *p*-values are summarized in Table 2. The *p*-values indicate that none of the models tested are above 0.05 and can approximate SREC prices at the 5% confidence level. At this point, more stochastic processes should be tested to find a better fit, but for illustrative purposes we will continue our analysis using the GBM simulation of future prices based on results from the QQ plots.

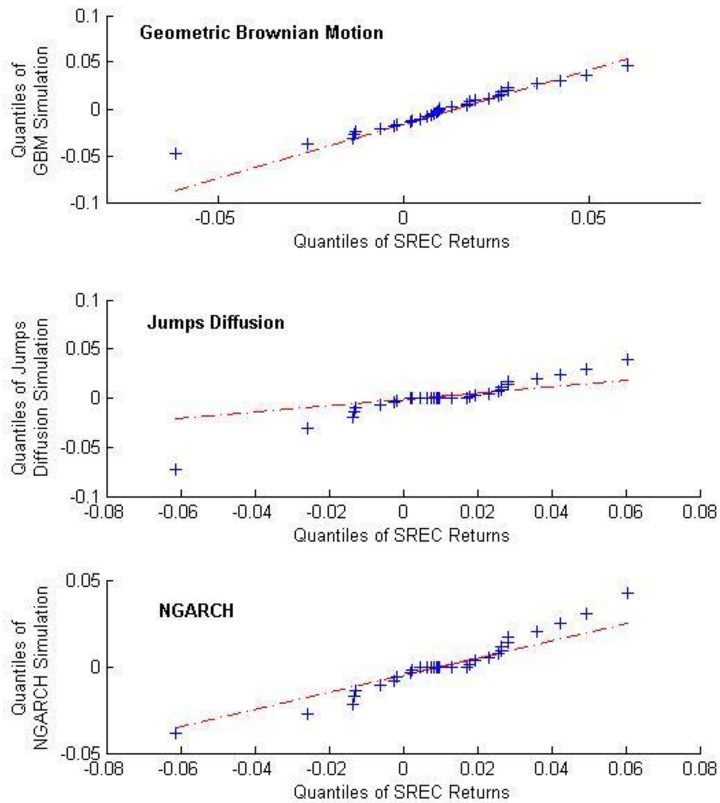

Figure 11. QQ plots of NJ SREC returns versus simulated returns with price cap.

Because of generous net-metering laws that allow customers to sell electricity back to the grid, roof-installed systems on residential, commercial and industrial roofs are very common. Thus our hypothetical system will be much smaller at 200kW and cost $1.1 million based on the per watt cost of $5.5 cited in a recent Lawrence Berkeley National Laboratory report (Barbose et al.,2011). The capacity factor for solar PV is much smaller than that of wind and we use an estimate of 18% for our example. Additionally, the conversion of DC watts (units of PV system size) into AC watts (units that qualify for SRECS) occurs around 95% efficiency. Combining both of them translates to 300 SRECs received per year. We use the same methodology as before to calculate bond prices, this time using simulations based on GBM. The histogram of simulated revenue bond prices is shown in Figure 12. On average, the bond contribution of US$ 1.26

million exceeds the total capital costs. The developer will not raise more money than necessary so we assume he sells US$ 1.1M worth of bonds, corresponding to 87.3% of future SREC revenue obligations, of US$ 1.1M. Next we isolated all simulated paths for which the return was under 7%. We then increased the yearly revenue for those paths to reflect that sales from all 300 SRECs will be used for repayment. If, for a particular path, the additional SRECs are able to increase the IRR to7%orhigher, we count the return as 7%. Otherwise, it will still be lower than the target return despite the added revenue. Our simulation shows that the risk of losses is 0%. (To be exact, 2 simulations out of our 10,000 gave negative returns) and that the risk of earning less than the expected IRR is only14.92%, compared with 50% without the safety netofextra revenue. The histogram of rate of return is shown in Figure 12 and details of risk analysis can be found in Table 3.

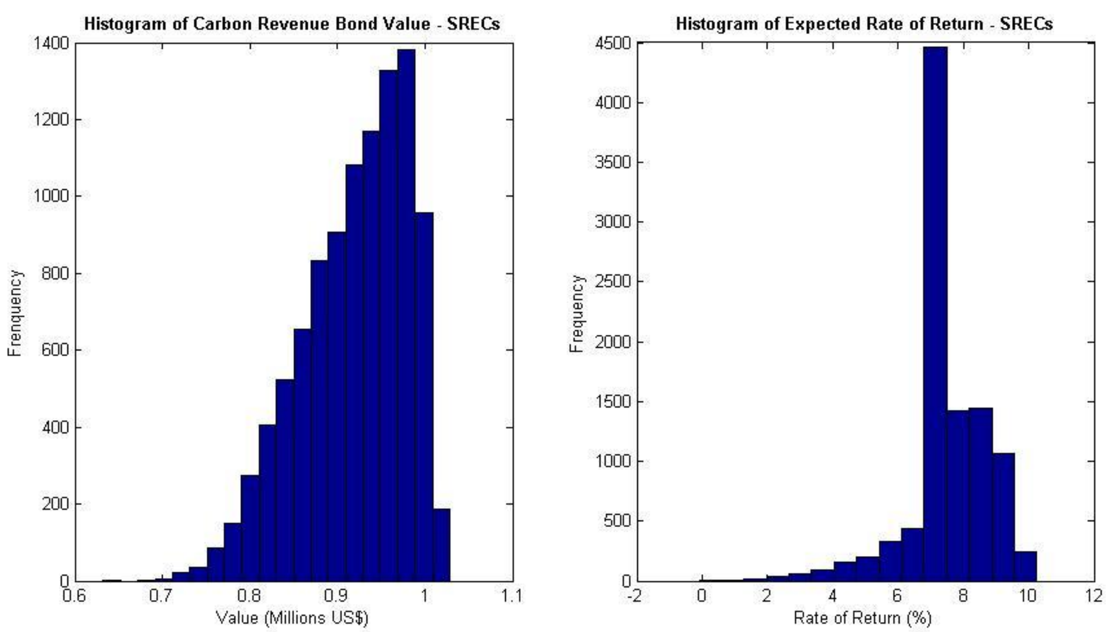

Figure 12. Histogram of bond value and histogram of expected return for NJ SRECs.

Table 2. Summary of Model Parameters.

		GBM	*NGARCH*	*Jumps Diffusion*
EUA	Parameters	μ = 1.2633e-4 σ = 2.0633e-2	μ = 1.1848e-4 ω = 3.3578e-4 α = 0.19643 β = 1.2817e-2 γ = 1.2150e-2	μ^* = 1.3639e-4 σ = 1.9695e-2 λ = 1.1342e-2 λ_μ = -4.4822e-2 λ_σ = 3.4943e-2
	p-value	0.67776	0.66602	0.70864
Australian RECs	Parameters	μ = 9.9289e-5 σ = 1.5665e-2	μ = 1.1754e-4 ω = 1.6345e-4 α = 0.19631 β = 1.2813e-2 γ = 1.2173e-2	μ^* = 9.9255e-5 σ = 9.4618e-4 λ =0. 9576 λ_μ = 1.2567e-4 λ_σ = 1.4321e-2
	p-value	1.1887e-009	6.2237e-009	0.050055
New Jersey SRECS	Parameters	μ = 1.1088e-2 σ = 2.2330e-2	μ = 1.0895e-2 ω = 4.3802e-4 α = 0.11151 β = 1.2432e-2 γ = 2.3645e-2	μ^* = 1.1096e-2 σ = 1.8321e-2 λ =3.2379e-2 λ_μ = -7.2046e-2 λ_σ = 2.8944e-5
	p-value (no cap) p-value (cap)	0.82378 1.9913e-3	0.79432 1.0062e-5	0.85069 5.1942e-6

Table 3. Results of illustrative examples and risk analysis.

		EUAs using Jumps Diffusion Model	*Australian RECs using Jumps Diffusion Model*	*New Jersey SRECs using GBM (with cap)*
Bond Value	**Median** *(% of initial cost)*	€ 30.2M (*15.1*)	AU$ 127M (*36.3*)	US$ 1.26M (*115*)
	Lower Quartile (Q1) *(% of initial cost)*	€ 20.0M (*10*)	AU$ 97M (*27.7*)	US$ 1.16M (*105*)
	Upper Quartile (Q3) *(% of initial cost)*	€ 46.4M (*23.3*)	AU$ 169M (*48.3*)	US$ 1.34M (*122*)
Risk Analysis[*]	**Expected Return (%)** [*Q1, Q3*]	7 [-*1.37, 15.80*]	7 [*1.41, 12.97*]	7 [*7, 8.3*][***]
	Risk of loss (%)[**]	28.59	20.19	0[***]

[*]Based on median bond value
[**]Negative return on investment
[***]Calculated using additional REC sales to hedge against lower prices

DISCUSSION AND CONCLUSION

These illustrative examples reveal that sale of a carbon revenue bond can help finance a meaningful portion of the initial capital cost of renewable energy infrastructure as summarized in Table 3. The median bond value or the average amount of revenue expected from ten years of credit sales ranges from 15.1% to 115% of initial costs. This is not insignificant considering that current treasury grants cover up to 30% of development costs. The upper and lower quartiles signify the range in which the amount of revenue collected could fall. In other words, there’s a 50% chance that future revenue will fall between the lower and upper quartile range. The same as been done for expected return, and investors can use that as a measure of risk. For example, the EUAs show the widest range, indicating a greater probability that revenue received will be different than initial investment and returns different than anticipated. The SRECs, on the other hand, have the smallest range, and hence a lower chance that future revenue will drastically vary from the initial bond value. The risk of loss calculated here represents the chance that the rate of return is negative, or the investment loses money. Investors may also wish to calculate the risk of returns below a certain threshold, such as 5%, in order to make careful decisions about how much risk they are willing to carry. Again, it should be noted that historical data for SRECs are limited and the results should be taken with that in mind. The examples are only intended as a demonstration of how to price a carbon revenue bond.

Since developers of non-renewable energy sources do not have access to the revenue stream from environmental credits, renewable energy developers who use this tool effectively decrease the cost of electricity production to help compete with conventional, cheaper generation methods such as coal or natural gas. A carbon revenue bond enhances regulatory measures and the markets that develop around them, such as RPS and REC trading, respectively. These policies do not directly help developers overcome the high initial cost of infrastructure as credits are awarded after the start of electricity production. Our idea of a carbon revenue bond securitizes the future revenue streams to provide a developer funds up-front, thus effectively defraying the high initial cost of development. In our hypothetical example involving New Jersey SRECs, a carbon revenue bond can finance up to 100% of capital costs. It is also an improvement on current US national, state or local level incentives including production credits, tax credits, and grants that expire quickly relative to the project life of renewable energy infrastructure. Studies have shown that the presence and expiration of PTCs have contributed to fluctuations in wind development, especially in Texas (Bird et al., 2005; Bolinger et al., 2009). Despite this, five out of the six primary financing structures used for wind development depend on tax equity investors (Bolinger et al., 2009). Although initially such structures were successful, the financial downturn has drastically lessened the pool of available and interested developers (Schwabe et al., 2009). Regulatory measures that do not involve direct government handouts but instead rely on market players to incentivize each other, such as RPS and carbon caps, tend to expire less quickly, as is the case with the three locations presented in our illustrative examples. It is reasonable to assume that the existence of markets for environmental credits surrounding these measures, and therefore the carbon revenue bond, is more stable relative to other government incentives. Because carbon revenue bonds can be used in conjunction with other incentives, developers can take advantage of all financing opportunities concurrently. It is also important to point out that a carbon revenue bond may be a *cheaper* financing tool for renewable energy projects than currently used structures. It is often cited that the cost of debt is lower than the cost of equity. Literature has shown that development of the same wind project using different financing structures leads to different levelized costs of electricity (Wiser, 1997). Future research can extend this analysis to include a carbon revenue bond in the cash flow models in order to quantitatively determine the potential savings.

Notwithstanding the aforementioned advantages, the carbon revenue bond carries an inherent amount of risk since future environmental credit prices cannot be known with 100% certainty. To predict future prices, we employ stochastic models which are commonly used for tradable assets (Schwartz, 1997). One major advantage of this method is that the inputs come only from historical data and not from assumptions of other variables, but the authors acknowledge the wide-spread use of other models as well. It should be noted that different renewable energy incentive schemes are best approximated by different processes. Even identically structured and operated RPS schemes in neighboring US states may have REC prices that are best forecast using different models. The behavior of the same environmental credit will also change over time. It is wise for developers to re-calibrate model parameters and test different models for each new project in the pipeline based on the most recent data available on the prices of the credits they expect to receive. As markets become more mature, improved models can be built to better forecast environmental credit prices.

Nevertheless, simulating prices using a stochastic process allows developers and investors to quantifiably evaluate the risk of the bond. That is, simulation results produce a mean number for the value of the bond, but also a distribution around that mean, so that the probability of loss can be calculated as was shown in our illustrative examples. While the inherent risk in a carbon revenue bond cannot be eliminated, only reduced, the remaining risk can be properly allocated across project participants. As presented in this paper, the structure of the bond places all of the risks and attributes all financial windfalls on the bond buyer, as future revenues, whatever they may be, are passed- through directly from the owner to the investor. If future prices are higher than projected, the bond will have been undervalued. The investor benefits financially from the extra proceeds, earning a much higher return than expected. Conversely, if future prices are lower than expected, then the bond has been overvalued and the investor will not receive the desired return on the bond.

Altering the structure of the bond is a good way to spread risk between the buyer and the seller of the bond. Introducing a coupon into the bond structure with the majority of repayment at maturity—this is how Treasury bills and many municipal bonds are structured—gives the owner the opportunity to invest revenue collected, which can mitigate some of the risk of lower than expected credit prices. Revenue from electricity sales can be used to hedge potential losses if not pledged to other lenders, effectively transferring price risk to the owner, but limited to the amount of electricity sales. This is a similar situation that we encountered in the illustrative example from New Jersey where left over SRECs were used to decrease the riskiness of the bond by a significant amount. Additionally, embedding options to exit the bond or renegotiate terms if future prices are drastically different than anticipated can ensure an investor return that is close to the expected return. Decreasing bond maturity can also decrease risk, as prices further into the future contain more uncertainty. This may be a good strategy for high-value environmental credits which provide a large portion of initial development costs if securitized, as is the case in the SREC example. Future research should examine the applicability of different bond structures as a risk allocation tool between the bond buyer and the bond seller in the context of a carbon revenue bond. Future research should also assess the relevance of the carbon revenue bond in differing market economies, most notably developing ones. Many countries qualify for the Clean Development Mechanism (CDM) under the Kyoto Protocol for which certificates are issued for an avoidance of additional carbon emissions as these countries grow. However, the electricity markets of these countries need to be studied to make sure the use of a project carbon revenue bond is appropriate and consistent with the way public infrastructure projects are delivered. Implemented well, the carbon revenue bond may promote increased renewable energy development, which is a critical part of the solution to the rise in global energy demand and need to reduce greenhouse gas emissions. Renewable energy development makes up 21% of the effort proposed by the International Energy Agency (2008) as being needed to meaningfully reduce greenhouse gas emissions. Future research on the carbon revenue bond and other stable financing mechanisms that reward the positive externality of reducing greenhouse gas emissions are needed for the research community to play an active role in increasing investments in renewable energy infrastructure. In doing so, researchers can help by providing sustainable solutions to rising worldwide energy demands and environmental pollution.

Chapter 3

STRATEGIC STRUCTURE MATRIX: A FRAMEWORK FOR EXPLAINING THE IMPACT OF SUPERSTRUCTURE ORGANIZATIONS ON THE DIFFUSION OF WIND ENERGY INFRASTRUCTURE[7]

ABSTRACT

Increasing the use of renewables in the global energy mix has become a top priority for policy makers. In this paper, we use a diffusion theory based approach to analyze the impact of government initiatives on the development of wind energy infrastructure focusing on the specific case of wind energy diffusion in India. We propose a new framework—the strategic structure matrix—as a way to characterize the strategic focus and analyze the effectiveness of different initiatives to increase wind power diffusion. We apply the matrix to explain the different pace and paths of wind energy growth observed in five Indian states: Tamil Nadu, Gujarat, Maharashtra, Andhra Pradesh, and Karnataka. Our findings suggest the importance of a comprehensive approach that includes multiple strategies across initiatives, local regulatory measures, and supply-side incentives.

INTRODUCTION

Concerns over climate change and environmental pollution have placed a strong emphasis on increasing the share of renewable energy technologies (RETs) in the world's energy

---

[7] This paper was co-authored with Professor John E. Taylor and Professor Ashwin Mahalingam. It is currently in the revision process at Energy Policy.

mix. In the past decade, great strides have been made to develop and use renewables for electricity production, heating and cooling, and transportation. In 2010, renewable sources generated 16.7% of total energy consumed worldwide, and wind capacity alone has increased from 6.1 gigawatts in 1996 to 238 gigawatts in 2011 (REN21, 2012). However, as demand for energy continues to increase, especially in developing countries where it has historically outpaced supply, there is an urgent need for greater inclusion of RETs.

The growth of renewable energy is aided by the policies and actions of various organizations, including local and national governments. However, some policy measures have led to greater development of renewable energy infrastructure than others, and the impact of the same initiative in different cities, states or nations are far from identical. It is important to understand why and under what conditions certain strategies have met with success, in order to better inform policy makers on designing initiatives to increase renewable energy use.

In this paper, we use a diffusion of innovation lens to analyze strategies used by organizations to promote diffusion. In the next section, we use past literature to develop a novel framework—the strategic structure matrix—to improve existing analysis of the impact of organizational initiatives on the pace of diffusion. The explanatory value of the matrix is tested by examining the initiatives used by government organizations in India to promote the development of wind energy infrastructure from 1992 to 2011. Section 3 presents the research setting and methodology, which begins with a country-wide overview and then narrows focus to five states: Tamil Nadu, Gujarat, Maharashtra, Karnataka and Andhra Pradesh. The results of our analysis of these five states are presented and discussed in Section 4. Section 5 contains the contributions and limitations of the paper, and offers suggestions for future research. Section 6 concludes the paper.

ORGANIZATIONS AND DIFFUSION

Using Rogers' (2003) definition, diffusion is "the process in which an innovation is communicated through certain channels over time among members of a social system" (Rogers, 2003, pg 5). Innovations are ideas, processes and technologies that are perceived as new by an adopter. Communication channels may include mass media and word of mouth through social networks. Lastly, the social system comprises of members who may be potential adopters. Much of diffusion research seeks to understand the factors that lead to adoption or non-adoption of an innovation, often with the ultimate goal of learning how to make it diffuse more quickly.

Research has shown that organizations, including governments, academic and research facilities, industry and trade associations, often play an important role in the diffusion of new technologies. For example, despite the prominence of Sony during the commercialization of the transistor radio in Japan, the Japanese Ministry of International Trade (MITI) and the government Electrotechnical Laboratories (ETL) helped establish a competitive market, diffused knowledge of the new technology, and demonstrated its technical capabilities before Sony entered the market (Lynn, 1998). These actions played a key role in successful diffusion. In another part of the world, a case study on the development and diffusion of biomass technologies in Austria identified fifteen organizations on the supply-side alone which shaped the spread of biomass boilers in the agricultural community, including the Chamber of Agriculture and the Regional Energy Association as two of the most influential (Rohracher, 2002). Their "intense promotional and networking efforts" were crucial in jump-starting diffusion during the initial phases. The next logical question is then, what is it about these organizations that make their actions so effective?

Innovation community framework

While many empirical studies examine organizations' involvement in diffusion, Lynn et al. (1996) found that there existed no analytical framework for identifying how relevant organizations affect the rate of diffusion or the path of such diffusion. Borrowing from the ideas of organizational ecology to find the boundaries of organizations involved in diffusion, they created the "innovation community" framework which allows classification of organizations into superstructure and substructure organizations. Substructure organizations are producers of the innovation or its technological components. They perform almost all economic research on the innovation. Superstructure organizations coordinate the flow of information and activities within the innovation community. They are usually non-market entities and include governments, research institutions, and professional or trade associations. Superstructure organizations are generally taken for granted in the literature on the diffusion process (Reddy and Rao, 1990) and therefore have not received much scholarly attention. In this paper, we will focus our attention on superstructure organizations and their role in diffusing renewable energy technologies.

Past research has shown that certain characteristics of a superstructure organization can determine its effectiveness in promoting innovation diffusion. Some characteristics include size, heterogeneity within the organization, basis of authority, level of centralization, and purpose (Howells, 2006; Lynn et al., 1996). Referring to the case studies mentioned earlier, the Chamber of Agriculture was able to take the role of a "system builder" in diffusing biomass technology in Austria because of its high basis of authority and its ability to influence other organizations (Rohracher, 2002). The success of Japan's ELT in aiding the commercialization of the transistor radio can be attributed to its purpose of advancing new technologies and leasing patents to various firms (Lynn, 1998). If the transistor had been developed by a single firm, it is unlikely that technical knowhow would have propagated as rapidly as it did.

While useful, analyzing a superstructure organization's characteristics does not singularly explain how it accelerates diffusion. A single organization may be involved in the diffusion of several innovations but with varied success, perhaps because of the different actions it chooses to take regarding each one. For example, India's Ministry of New and Renewable Energy recently had many initiatives to promote development of both wind and solar power. Despite findings that its initiatives contributed to early growth of wind energy (Rao and Kishore, 2009), analysis of the 2003 National Solar Mission found that it slowed growth of solar industries in certain areas and predicts that it will negatively impact future diffusion of decentralized solar applications (Harish and Raghavan, 2011; Raghavan et al., 2010). Additionally, superstructure organizations with similar traits may have different success with their initiatives. Therefore it is also important to look at the specific actions of superstructure organizations and the strategies they use in aiding innovation diffusion.

Increasing the focus on strategy

Few researchers have examined the strategic focus of initiatives employed by superstructure organizations and their role in innovation diffusion. After reviewing existing literature, the authors have identified five key categories of strategies: lowering a diffusion barrier, empowering an actor type, enabling an environment necessary for diffusion, targeting the technology or the support infrastructure, and affecting supply or demand. We now describe each of these categories in greater detail.

Lowering a diffusion barrier

Data collected during a 2012 interview with a researcher from the World Resources Institute classified the three major barriers to technological diffusion as technological, financial and regulatory. Technological barriers prevent a new technology and its support infrastructure from functioning properly or adapting to local conditions. Additionally, "technological lock-ins" can occur, in which the dominance of incumbent technologies prevent wide-spread use of innovative technologies (Foxon and Pearson, 2008). Funding for research and developing demonstration projects would be examples of initiatives aimed at overcoming technical hurdles. Financial barriers are ones in which the cost of or access to capital limit the commercialization of a technology for wide-spread use. Wind power in India is a more expensive technology for electricity production than many of its competitors, including fossil fuel-based generation methods, giving it a competitive disadvantage (Sargsyan et al., 2010). A United Kingdom case study also found evidence that the promotion of innovation is at odds with the economic efficiency of existing technology (Foxon and Pearson, 2008). Tax credits or access to low interest loans correct this disadvantage and reduce financial barriers for developers. Lastly, regulatory barriers slow down the diffusion process from a legal and/or political standpoint. Streamlining the approval process for adoption of a new technology or lifting a previous ban are both initiatives with the strategy of lowering regulatory barriers.

A recent World Bank report (Sargsyan et al., 2010) identified several remaining barriers to wide-spread adoption of wind energy infrastructure in India. Similar to the barriers discussed above, there are three main categories—financial viability, regulatory approvals, and support infrastructure. While the technological capability of wind turbines themselves have advanced over the past couple of decades, inadequate surrounding support infrastructure such as substations and the electrical grid remain as technological barriers to diffusion. Therefore characterizing an initiative based on which diffusion barrier it overcomes the most is an important step in determining its strategic focus.

Empowering actors

In addition to overcoming a diffusion barrier, initiatives from superstructure organizations can empower different types of actors in the diffusion community. A comparative analysis on regional innovation policies in seventeen Spanish regions (Fernandez de Lucio et al., 2010) found three types of strategies, each emphasizing different actors in the innovation community. The linear strategic model posits that innovation starts in a laboratory and eventually moves into a self-created market for commercialization. Policies adhering to this model, for example funding research laboratories, empower people and organizations working on the research and development of the innovation. The second type of strategy places emphasis on systems and market infrastructure, with policies promoting actors involved in creating a sound supporting network around the innovation, including intellectual property regulations, and market competition. The third type recognizes the importance of mutual knowledge and learning processes. Policies are aimed at coordinating activities between members of the diffusion community to strengthen ties and promote knowledge sharing. An R&D and innovation indicator was also calculated for each of the seventeen regions. While most regions are using policies defined best as the linear model, three out of the four regions with the highest R&D and innovation indicators have policies targeted mainly at increasing mutual knowledge and learning, suggesting a greater effectiveness over other types of strategies. Consistent with this finding, the linear model is increasingly being abandoned in favor of a more dynamic view of innovation

(Foxon and Pearson, 2008). In adding this category to the diffusion barriers discussed earlier, we provide an extra dimension through which to view initiative strategies.

Creating an enabling environment

Some researchers suggest certain enabling environments are precursors to successful diffusion. We identify and classify three types of strategies from past literature to this end: allowing for institutional change, creating or expanding markets, and formation or strengthening of advocacy coalitions. In one study, Jacobsson and Lauber (2006) examined the diffusion of wind turbines and solar cells in Germany. This was the first empirical study of an earlier framework (Jacobsson and Bergek, 2004), which postulated that four conditions are necessary to promote renewable energy growth: institutional change, market creation, advocacy coalitions and entrance of new firms. In this paper, we have combined market creation and entrance of new firms into one strategy category as both bring new players into the market, just at different times during the diffusion process. The empirical study found that all four conditions were present, even if weakly, in the initial phase of diffusion for both wind and solar. Demonstration projects, for example, enabled new markets to form by boosting private sector participation. A feedback loop was also identified in which the results of one strategy led to subsequent promotion of other strategies. For example, the new markets created from the demonstration projects led to more influential advocacy coalitions, which in turn lobbied for better legislation to create institutional change. These enabling environments are relevant to any of the diffusion barriers and empowered actors detailed above, adding yet another level of detail to characterization of superstructure organization initiatives.

Direct or indirect influence

Systematic innovations like centralized wind power depend on support infrastructure such as substations and the electrical grid in order to operate. Some initiatives intended to help diffusion of the innovation actually bolster the support infrastructure. Research has identified the importance of such infrastructure for wind power and renewable energy more broadly as well (Brown and Hendry, 2009; Sargsyan et al., 2010). Including this difference allows us to include initiatives which target support networks for a new innovation but ultimately lead to higher rates of adoption of the innovation itself. For example, as we will discuss later in the case study, Maharashtra addressed financial issues of complementary infrastructure such as substations and access roads to encourage increases to wind energy capacity. We therefore classify actions in this strategy category as “direct” or “indirect” to indicate whether the initiative in question affects the innovation directly, or indirectly through support infrastructure.

Demand or supply

Literature has also classified initiatives as either acting on the demand side or the supply side. Brown and Hendry (2009) analyzed government programs which promoted diffusion of photovoltaic in the US, Japan, and Europe, and refer to the “technology-push/market-pull” nature of government policy. Similarly, in his study of the growth of wind energy in California in the 1980s and 1990s, Nemet (2009) separated government strategies into “demand-pull” and “technology-push” actions. Demand-pull actions are those that raise the pay-off for successful innovations, including tax credits and rebates, technology mandates and direct government procurement of the technology. Technology-push initiatives reduce costs associated with innovation, including funding research and development, easing knowledge exchange and setting up demonstration projects. Nemet (2009) shows that the timing of diffusion coincides with the period when generous tax credits were available to developers in California. Combined with evidence that unsubsidized wind energy production was not profitable until the 2000s while the bulk of capacity was installed in the mid-1980s, he finds support for the favorable effect of demand-pull policies on wind power diffusion. However, several of these demand-pull policies were enacted by the US federal government and applied to all states. There may be variations in state policies which have led to diverse diffusion patterns for wind power in different states. Texas, for example, experienced its wind boom much later.

Formulation of the strategic structure matrix

While past studies have identified and examined strategies used by organizations to speed up diffusion, they do not simultaneously characterize different categories of strategies. For example, an initiative that lowers a financial barrier to diffusion can simultaneously increase demand for the technology, yet no framework exists to analyze these two characteristics concurrently. Therefore in order to synthesize the disparate studies mentioned above and to provide greater insight into the effect of various strategies used by superstructure organizations on innovation diffusion, we formulated a strategic structure matrix in order to describe the actions of superstructure organizations. Table 4 displays the matrix and explains the different characterizations, which have been adapted from previous literature on diffusion and technological change.

Each initiative can be described by a combination of five strategies—its strategic structure—one from each category. A demonstration project, for example: overcomes technical barriers; empowers people/institutions involved in research and development; helps create a new market; directly targets the technology in question; and acts on the supply side of diffusion. By using a matrix instead of a one-dimensional analysis as in previous studies, we are able to gain a more nuanced understanding of the characteristics of initiatives used to promote diffusion and their outcomes. The classification offered by the strategic structure matrix will better explain why certain initiatives succeed while others do not, and also help build theory on which combinations of strategies are most effective with respect to renewable energy technologies. Our purpose in developing this new framework is to address the gap in existing literature and to better understand how to effectively develop policy aimed at increasing the speed of diffusion of renewable energy technologies.

Table 4. Strategic structure matrix.

Lowering a Diffusion Barrier	*Empowering Actors*	*Creating an Enabling Environment*	*Direct or Indirect Influence*	*Supply or Demand*
Technical: decreases uncertainty with technical capabilities *- or -* **Financial**: decreases cost or increases future value *- or -* **Regulatory**: decreases regulatory hurdles to diffusion	**R&D**: increases support of research laboratories and organizations developing new technologies *- or -* **Systems and Infrastructure**: provides support for surrounding infrastructure (physical, market, etc.) *- or -* **Knowledge and learning**: strengthens ties between facilitating organizations	**Institutional Change**: improves institutional landscape for easier diffusion of the technology *- or -* **New/Expanded Market**: creates a new market or expands existing market *- or -* **Advocacy coalition**: creates or promotes pro-diffusion organizations	**Direct**: targeted primary at technology being diffused *- or -* **Indirect**: targeted primary at infrastructure surrounding the technology	**Supply**: ultimately decreases costs or lowers barriers associated with adoption of the technology *- or -* **Demand**: ultimately raises the payoff after adoption of the technology

RESEARCH SETTING AND METHODS

Strategic structure matrix case study

The application of this matrix can help address the broader question of how superstructure organization strategies affect the diffusion of technologies. As a step in this direction, we test our matrix by performing a case study of the growth of wind energy in India and analyze the differences in the strategic structure of initiatives used by various superstructure organizations in the diffusion community, and their outcomes. More specifically, we investigate the actions of the Central Government and five state governments which have positively affected the growth of wind power in India. Government organizations are a subset of superstructure organizations in general. They are unique in their ability to bring regulatory authority and legitimacy behind the incentives they offer. We focus on incentives by governments and their related organizations in this paper to control for the level of authority an organization has when trying to increase innovation diffusion. We aim to discover: 1) if better characterization offered by the strategic structure matrix can explain the fast growth of wind energy in some states and the slow growth in others; and 2) the relative effectiveness of strategies or combinations of strategies in promoting wind energy diffusion in India. In doing so, we hope to pinpoint favorable strategic structures in order to guide future actions of superstructure organizations concerned with diffusing renewable energy.

Case study setting – wind power in India

In 1983, the Ministry of Non-conventional Energy Sources (MNES) (currently the Ministry of New and Renewable Energy (MNRE)) started the Wind Energy Programme under the Central Government of India with the broad goals of assessing wind resources, building demonstration projects and creating industry-utility partnerships (Bhattacharya and Jana, 2009; Pillai and Banerjee, 2009; Rajsekhar et al., 1999). Since then, this and other initiatives have helped wind energy grow considerably and India currently ranks fifth in installed capacity worldwide. Even its potential seems to grow. A recent study by Lawrence Berkley National Laboratory (Phadke, 2011) reassessed the wind energy potential in India and found it to be much higher than previous estimates, suggesting additional room for expansion. The study also found that ninety-five percent of India's wind power potential lies in five states: Tamil Nadu, Gujarat, Maharashtra, Andhra Pradesh and Karnataka.

While blessed with natural wind resources, these five states have had mixed success in harnessing its power for energy. Figure 13 shows how much of its wind power potential each state has harnessed through installation of wind turbines from 1992 to 2011. Diffusion theory postulates that when the adoption of an innovation is plotted against time, the resulting diffusion curve will be s-shaped (Rogers, 2003). It appears that all five states are still in the early phases of diffusion. Even so, the differences between the states can be clearly observed. For example, Tamil Nadu has consistently led development while Karnataka's growth has lagged behind the rest. A divergence in the diffusion curves can be observed around 2004-2005, further suggesting a growing difference in wind power adoption among the states.

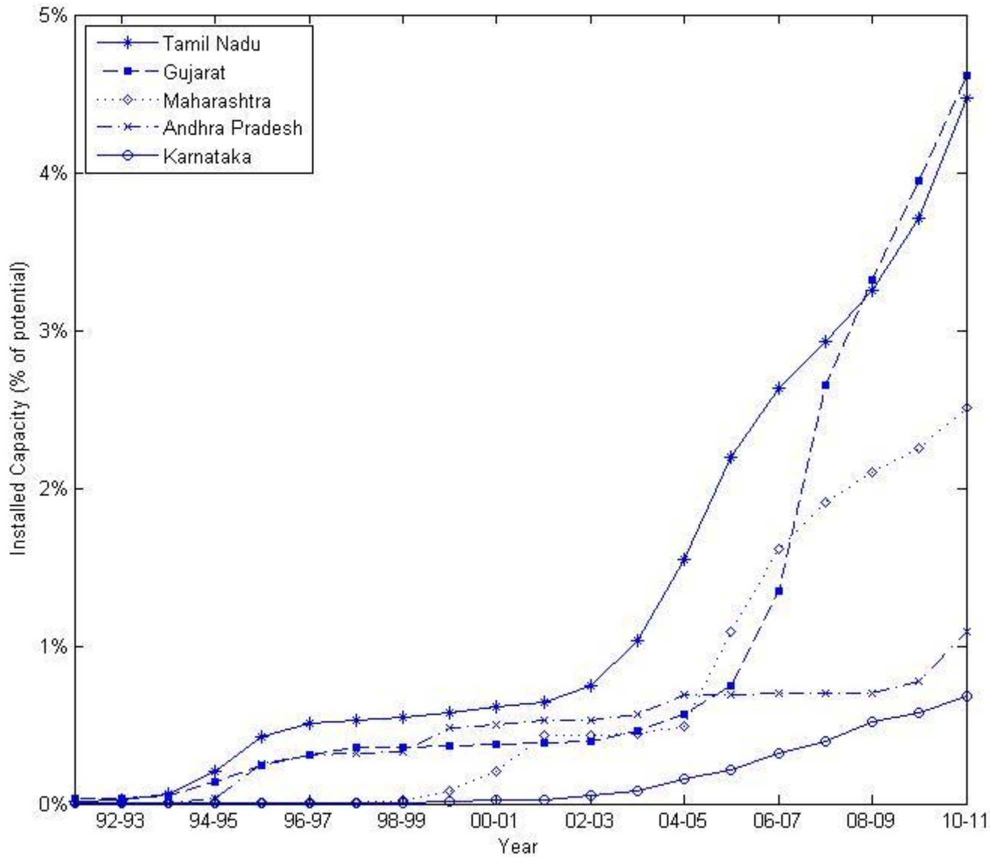

Figure 13. Installed capacity of wind energy generators from 1992 to 2010-2011.

Since individual states in India have a great deal of autonomy in managing their power sector, the differences in the growth of their wind energy may be in part due to variations in state level policies and strategies and how well those complement national incentives. After first identifying the initiatives used to encourage adoption of wind power, we use the strategic structure matrix as a tool to analyze the differences between them to examine whether the strategic structure of the initiatives can help explain similarities and differences in the patterns of diffusion between states.

Quantitative diffusion curve modeling

The diffusion curves in Figure 13 were created using data from MNRE annual reports and information published by nodal agencies responsible for renewable energy in individual states. The raw data from those reports was used to determine the percentage of wind power potential achieved for each state as measured in a recent Lawrence Berkley National Laboratory report (Phadke, 2011) for fair comparative analysis.[8] Table 5 lists the wind power potential for each state as well as additional information on state characteristics. Taken together, a state's area, total population and percentage of urban population are indicators of its electricity needs; its per capita GDP is a proxy of its socio-economic progress. The states are comparable among these characteristics and also rank in the top half of all Indian states, suggesting that a single state's success in achieving a higher percentage of its wind energy potential cannot be attributed to a greater demand for electricity or better socio-economic status.

Table 5. Wind power potential and other characteristics of selected Indian states.

State	*Wind Power Potential*		*Area*		*Population*		*Urban Population*		*Per Capita GDP*	
	MW	*Rank*	*[km^2]*	*Rank*	*[millions]*	*Rank*	*[%]*	*Rank*	*[USD]*	*Rank*
Tamil Nadu	131,500	2	130,058	11	72.1	7	44.0	3	1,587	9
Gujarat	47,200	4	196,024	7	60.4	10	37.4	5	1,728	7
Maharashtra	92,100	3	307,713	3	112.4	2	42.4	4	1,850	4
Andhra Pradesh	17,600	5	275,045	4	84.7	5	27.3	10	1,527	11
Karnataka	255,100	1	191,791	8	61.1	9	34.0	6	1,365	14

Note: Rank indicates a state's position among the 28 Indian states and 7 union territories in that category.

[8] The wind power potential numbers used in this paper are the most conservative estimates, in which wind potential is measured at 80m and potential over farmland is not included. For methodology of the potential calculated, see Phadke (2011).

The yearly growth of installed capacity of wind power is also calculated in order to identify years when wind energy development was especially successful, using the following equation:

$$\text{growth}_t = \frac{\text{capacity}_t - \text{capacity}_{t-1}}{\text{capacity}_{t-1}}$$

where t = year.

Figure 13 shows that additions to installed capacity stagnate around 1996 for all states before increasing again several years later. Additionally, previous literature has emphasized the importance of Central Government initiatives in the early years, and the promotional efforts by the states which led to increased wind energy development starting around 1999 (Bhattacharya and Jana, 2009). Therefore we separate the period of analysis into an earlier diffusion phase and a later diffusion phase for more detailed analysis. Since each state has a distinct pattern of diffusion and introduced state-specific initiatives to promote wind power development in different years, the start of the later phase varies. In order to determine the time periods of the later phase for each state, the Bass mixed-influence model (Bass, 1969; Mahajan and Peterson, 1985) was used to find theoretical diffusion equations and curves based on empirical data of installed capacity.

The Bass mixed-influence model describes diffusion over time as a function of both external and internal influences, represented mathematically using two coefficients, the coefficient of external influence and the coefficient of internal influence. It has been used in the past to model solar energy market penetration (Mahajan and Peterson, 1985). Graphically, the diffusion curve is s-shaped, with the rate of diffusion over time dependent on the coefficients, the total population of potential adopters, and the level of adoption at the start of the diffusion process. For the same values of potential adopters and initial level of adoption, faster diffusion is represented by larger coefficients of internal and external influence. The model has a discrete solution of:

$$N(t) = \frac{\bar{N} - \frac{a(\bar{N} - N_0)}{a + bN_0} \exp\left(-\left(a + b\bar{N}\right)(t - t_0)\right)}{1 + \frac{b(\bar{N} - N_0)}{a + bN_0} \exp\left(-\left(a + b\bar{N}\right)(t - t_0)\right)}$$

with $N(t)$ = cumulative adoption installed at time *t*,
N_0 = level of adoption at beginning of diffusion,
$\bar{N}$ = population of potential adopters,
a = coefficient of external influence,
b = coefficient of internal influence,
t = time,
and t_0 = time at start of diffusion .

Essentially, the Bass mixed-influence model is a three-parameter model: *a*, *b*, and $\bar{N}$. The other inputs are provided by empirical data. In our case, we are also able to fix $\bar{N}$ for each state by using the wind potential estimates from the Lawrence Berkley National Laboratory report (Phadke, 2011), reducing it to a two-parameter model, *a* and *b*, the coefficients of external and internal influence, respectively. Therefore only two data points per state are required to find the theoretical diffusion curves. Since we have more than two values, non-linear regression analysis was performed in MATLAB in order to find the parameter values that best fit the empirical data of installed capacity of wind energy. Residuals were also calculated to measure the goodness-of-fit of the theoretical diffusion curves to the empirical data. In order to determine the time period of the second phase of diffusion, different pairs of values of t_0 and N_0 were used to determine their associated diffusion curves with parameters *a* and *b*. The t_0 resulting in the lowest residual between the empirical data and the theoretical curves was chosen as the starting year for the later phase of diffusion. The results are in Table 6.

Table 6. Time periods of the early and later phase of diffusion for each individual state.

	Earlier Diffusion Phase	*Later Diffusion Phase*
Tamil Nadu	92 to 00-01 (9 years)	00-01 to 10-11 (10 years)
Gujarat	92 to 01-02 (10 years)	01-02 to 10-11 (9 years)
Maharashtra	92 to 02-03 (11 years)	02-03 to 10-11 (8 years)
Andhra Pradesh	92 to 02-03 (11 years)	02-03 to 10-11 (8 years)
Karnataka	92 to 01-02 (10 years)	01-02 to 10-11 (9 years)

By separating the period of analysis into two phases, we are able to discover why the Central Government initiatives introduced in the initial diffusion phase had a greater impact in certain states. The lack of major initiatives applied at a national level in the later diffusion phase allows us to pinpoint state-specific strategies and how they impacted wind power growth in each of the five states individually.

Qualitative data collection to complement diffusion curve analyses

In order to determine central and state government initiatives that have positively influenced the development of wind energy, we first reviewed secondary sources on renewable energy in India, including scholarly articles, publicly available reports from government agencies and independent research institutions, and newspaper articles. A preliminary list of initiatives was compiled.

Interviews were then conducted with the organizations responsible for creating the initiatives and the parties who subsequently used them to develop wind power. Interviewees included past and present government officials from MNRE, state nodal agencies, the Center for Wind Energy Technology, as well as major wind turbine manufacturers and energy developers. An effort was made to speak with government officials involved in wind power development from each state. For states where this was not possible, state-specific questions were asked to officials who participated at a national level and interviews were conducted with researchers familiar with the wind energy sector of that state. The renewable energy technology manufacturers and developers interviewed have collectively operated in all of the five states studied. A total of twelve people were interviewed for a total of approximately thirty hours between October 2011 and May 2012 in India. Some were interviewed more than once. Copious notes were taken during the interviews and any questions were later clarified through email correspondence.

The interviews helped clarify any inconsistencies in the aforementioned secondary sources and refine the preliminary list of initiatives to the one presented in this paper. Additionally, speaking with a wide variety of actors in the diffusion community helped offer a holistic view and decreased bias in the data collected. Information gathered during the interviews together with analysis of the secondary sources informed classification of observed initiatives using the strategic structure matrix. The results are shown in Table 7. In the initial phase, some states had promotional efforts in place to encourage wind energy development by the time national level incentives were introduced in the early 1990s. The collective strategies of central and state-level incentives are analyzed for each state in order to discover if similarities exist in the strategic patterns for states in which installed capacity of wind power increased during this period. The same is done for states in which wind development did not increase significantly, and differences between the strategic patterns of the two sets of states are also examined. In the later phase, the timings of the initiatives were compared to the diffusion curves and yearly growth curves to evaluate their effect, if any, on increasing wind power development and how their strategic structure may have had an impact. A strategic profile of all later phase initiatives is also provided for each state. In validating the explanatory value of the strategic structure matrix, similar strategic patterns of initiatives enacted in different states at different times should have similar effects on the states' diffusion curves at their respective times.

Table 7: Initiatives to promote wind power and their strategic structures.

	Date(s)	*Initiative*	*Barrier*	*Actor*	*Environment*	*Direct/ indirect*	*Supply/ demand*
Central Government	***Early 90s***	***Accelerated depreciation***	Financial	Systems and infrastructure	Market	Direct	Demand
	Early 90s	***Low or no tariff for imported parts***	Financial	Systems and infrastructure	Market	Direct	Supply
	Early 90s	***Loans from IREDA***	Financial	Systems and infrastructure	Market	Indirect	Supply
Tamil Nadu	***1985***	***Formation of nodal agency (TEDA)***	Regulatory	Knowledge and learning	Institutional change	Indirect	Supply
	86-93	***Demonstration projects***	Technical	R&D	Market	Direct	Supply
	1998	***CWET headquarters***	Technical	Knowledge and learning	Advocacy coalition	Direct	Supply
	2004	***Captive Generation***	Regulatory	Systems and infrastructure	Institutional change	Indirect	Demand
Gujarat	***1979***	***Formation of nodal agency (GEDA)***	Regulatory	Knowledge and learning	Institutional change	Indirect	Supply
	86-92	***Demonstration projects***	Technical	R&D	Market	Direct	Supply
	2007	***Comprehensive wind energy policy***	Regulatory	Knowledge and learning	Institutional change	Direct	Supply
Maharashtra	***1986***	***Formation of nodal agency (MEDA)***	Regulatory	Knowledge and learning	Institutional change	Indirect	Supply
	94, 96, 99, 03, 04	***Demonstration projects***	Technical	R&D	Market	Direct	Supply
	2004	***Renewable energy policy***	Regulatory	Knowledge and learning	Institutional change	Direct	Supply
	2004	***"Green energy fund"***	Financial	Systems and infrastructure	Market	Indirect	Supply
Andhra Pradesh	***1986***	***Formation of nodal agency (NEDCAP)***	Regulatory	Knowledge and learning	Institutional change	Indirect	Supply
	94, 01, 04	***Demonstration projects***	Technical	R&D	Market	Direct	Supply
	Mid 90s	***Wind estate laws***	Regulatory	Systems and infrastructure	Institutional change	Indirect	Supply
	2008	***Renewable energy policy***	Regulatory	Knowledge and learning	Institutional change	Direct	Supply
Karnataka	***1996***	***Formation of nodal agency (KREDL)***	Regulatory	Knowledge and learning	Institutional change	Indirect	Supply
	03, 04	***Demonstration Projects***	Technical	R&D	Market	Direct	Supply
	2009	***Renewable energy policy***	Regulatory	Knowledge and learning	Institutional change	Direct	Supply

FINDINGS

Initial diffusion phase

In the early 1990s, development of wind energy infrastructure was primarily encouraged by the Central Government. The most frequently mentioned incentive is accelerated depreciation, in which developers can depreciate 100% (later decreased to 80%) of the value of wind generation assets in the first year of operation. With the allowance of private investment in electricity generation assets, many new parties entered the wind energy market to take advantage of accelerated depreciation in the early 1990s. Many of these developers were large corporations who were able to take advantage of the full tax benefits. In fact, a 1996 survey of wind developers found that a majority of wind developers were motivated primarily by tax savings (Pillai and Banerjee, 2009; Rajsekhar et al., 1999). The government also introduced low or no tariffs on imported wind energy generation technology and parts. Since technology was already being produced successfully in other countries, the tariff policy coupled with liberal foreign investment policies decreased the cost for developers when the domestic manufacturing industry was still nascent. Since wind power was new and relatively untested in India at this time, it was perceived as a risky investment by many banks. Indian Renewable Energy Development Agency (IREDA) was established in 1987 to provide financing to developers of wind projects. The establishment of IREDA instilled confidence in the economic viability of wind power, and private banks later started lending to developers.

However, even after accounting for wind energy potential, a disproportionate amount of developers chose to take advantage of the Central Government initiatives in Tamil Nadu and Gujarat, as shown in Figure 14. A clear gap is visible between the installed capacity in Tamil Nadu and Gujarat compared with the other three states in 1993-1994. We use the strategic structure matrix to explain this difference. In Table 8, we mark the strategic areas covered by each individual state at the time the national incentives were introduced using an "X". Each "X" represents one initiative. Similarly, we use a "Y" to mark the strategic areas covered by the three Central Government initiatives described above.

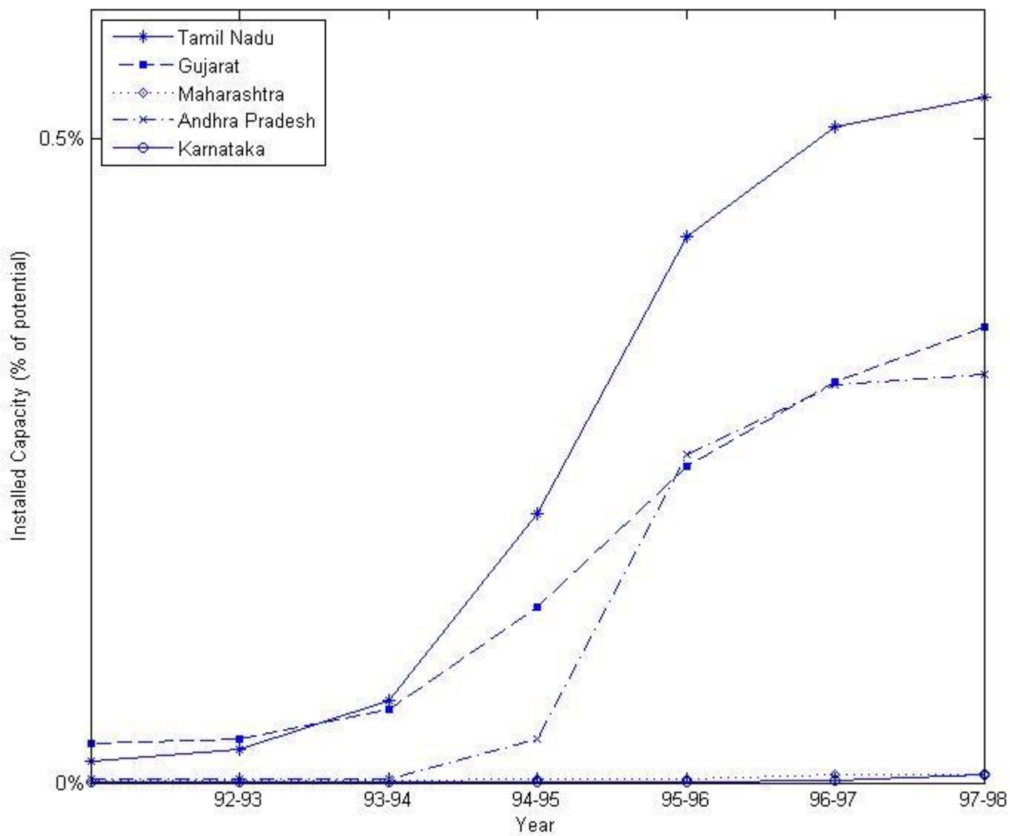

Figure 14. Installed capacity of wind energy generators from 1992 to 1997-1998.

Table 8. Strategies covered by various government initiatives in the early 1990s.

<table>
<tr><th></th><th></th><th>Tamil Nadu</th><th>Gujarat</th><th>Maharashtra</th><th>Andhra Pradesh</th><th>Karnataka</th></tr>
<tr><td rowspan="3">Barrier</td><td>Technical</td><td>X</td><td>X</td><td></td><td></td><td></td></tr>
<tr><td>Financial</td><td>YYY</td><td>YYY</td><td>YYY</td><td>YYY</td><td>YYY</td></tr>
<tr><td>Regulatory</td><td>X</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td rowspan="3">Actor</td><td>R& D</td><td>X</td><td>X</td><td></td><td></td><td></td></tr>
<tr><td>Systems and Infrastructure</td><td>YYY</td><td>YYY</td><td>YYY</td><td>YYY</td><td>YYY</td></tr>
<tr><td>Knowledge and Learning</td><td>X</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td rowspan="3">Environment</td><td>Institutional Change</td><td>X</td><td>X</td><td>X</td><td>X</td><td></td></tr>
<tr><td>Market Creation</td><td>X
YYY</td><td>X
YYY</td><td>YYY</td><td>YYY</td><td>YYY</td></tr>
<tr><td>Advocacy coalitions</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Direct/ Indirect</td><td>Direct</td><td>X
YY</td><td>X
YY</td><td>YY</td><td>YY</td><td>YY</td></tr>
<tr><td>Indirect</td><td>X
Y</td><td>X
Y</td><td>X
Y</td><td>X
Y</td><td>Y</td></tr>
<tr><td rowspan="2">Supply/ Demand</td><td>Supply</td><td>XX
YY</td><td>XX
YY</td><td>X
YY</td><td>X
YY</td><td>YY</td></tr>
<tr><td>Demand</td><td>Y</td><td>Y</td><td>Y</td><td>Y</td><td>Y</td></tr>
</table>

The top three categories of the strategic structure matrix are the most interesting. The two states that performed best in the early 1990s, Tamil Nadu and Gujarat, had initiatives in place which collectively addressed almost all strategies in each category. Namely, they both had completed demonstration projects which proved that wind energy was technically viable, empowered the research and development of the technology, and created a market for wind (the end of demonstration projects in 1992 and 1993 by Gujarat and Tamil Nadu, respectively, meant that the state believed that the technology was ready for commercialization, i.e., private investment). Additionally, as a radically different technology for energy production, wind power is more likely to be adopted by new energy developers rather than the same developers of traditional power generators (Lynn, 1998). It follows that the demonstration projects served as important market growth initiatives to draw new players into the energy market. Maharashtra, Andhra Pradesh and Karnataka had not yet under taken demonstration projects. In fact, Karnataka's first demonstration project was not built until 2003, over twenty years after implementation of the initial Central Government initiatives. This finding is consistent with past literature. Brown and Hendry (2009) found that the success of financial incentives is dependent on technology readiness, which varied from state to state in India in the early 1990s.

Additionally, Karnataka's state nodal agency for renewables, Karnataka Renewable Energy Development Limited (KREDL), was not formed until 1996 following a Central Government order for states to set up nodal agencies to promote wind energy. Its counterparts, Tamil Nadu Energy Development Agency (TEDA), Gujarat Energy Development Agency (GEDA), Maharashtra Energy Development Agency (MEDA), and New and Renewable Energy Development Corporation of Andhra Pradesh (NEDCAP), were started much earlier (see Table 7). According to the strategic structure matrix, formation of state nodal agencies decreases uncertainty about regulatory support, encourages mutual knowledge and learning, and creates a more favorable institutional environment. Although some of their actions may directly impact wind technology, their formation represents support for the surrounding infrastructure, which ultimately decreases non-financial costs for developing wind energy, for example, time spent navigating regulatory hurdles.

The demonstration projects and the creation of state nodal agencies served as necessary support for usage of the Central Government financial incentives. Supporting past literature (Fernandez de Lucio et al., 2010; Jacobsson and Lauber, 2006), Table 8 implies that incentives used to promote diffusion need to collectively cover all strategic areas in order to be successful.

This seems to hold especially true for a systemic innovation such as wind power. For example, in the “empowered actor” category of the strategic structure matrix, if research laboratories create an extremely efficient and inexpensive wind turbine and the state nodal agency shares and promotes it to energy developers, diffusion will be stunted if the supporting grid infrastructure is inadequate. The data also implies that advocacy coalitions may not be as critical during the initial phase of diffusion.

Later diffusion phase

Development of wind power slowed in 1996, which can be attributed to the introduction of the Minimum Alternative Tax (MAT). This tax required corporations to pay at least 12.9% tax on profits even if the depreciation of wind assets decreased taxes below that level. Effectively negating some of the benefits of accelerated depreciation, passage of the MAT caused investor interest to wane (Rajsekhar et al., 1999). Continued growth of wind energy infrastructure several years later can be attributed largely to individual state efforts (Bhattacharya and Jana, 2009) as well as the Electricity Act of 2003, which called for industry-wide reform of generation, transmission and distribution sectors (Bhattacharyya, 2005). Figure 15 plots yearly growth of installed capacity overlaid on top of cumulative installed capacity for the later phase, as defined previously in Table 6. With the exception of Karnataka, there is a general correlation between the presence of an initiative and increased growth one or two years later, since the highest values of percentage growth occur one or two years after a state enacts an initiative. Table 9 displays the strategic structure matrix for incentives introduced during the second phase of diffusion for all states excluding Karnataka.

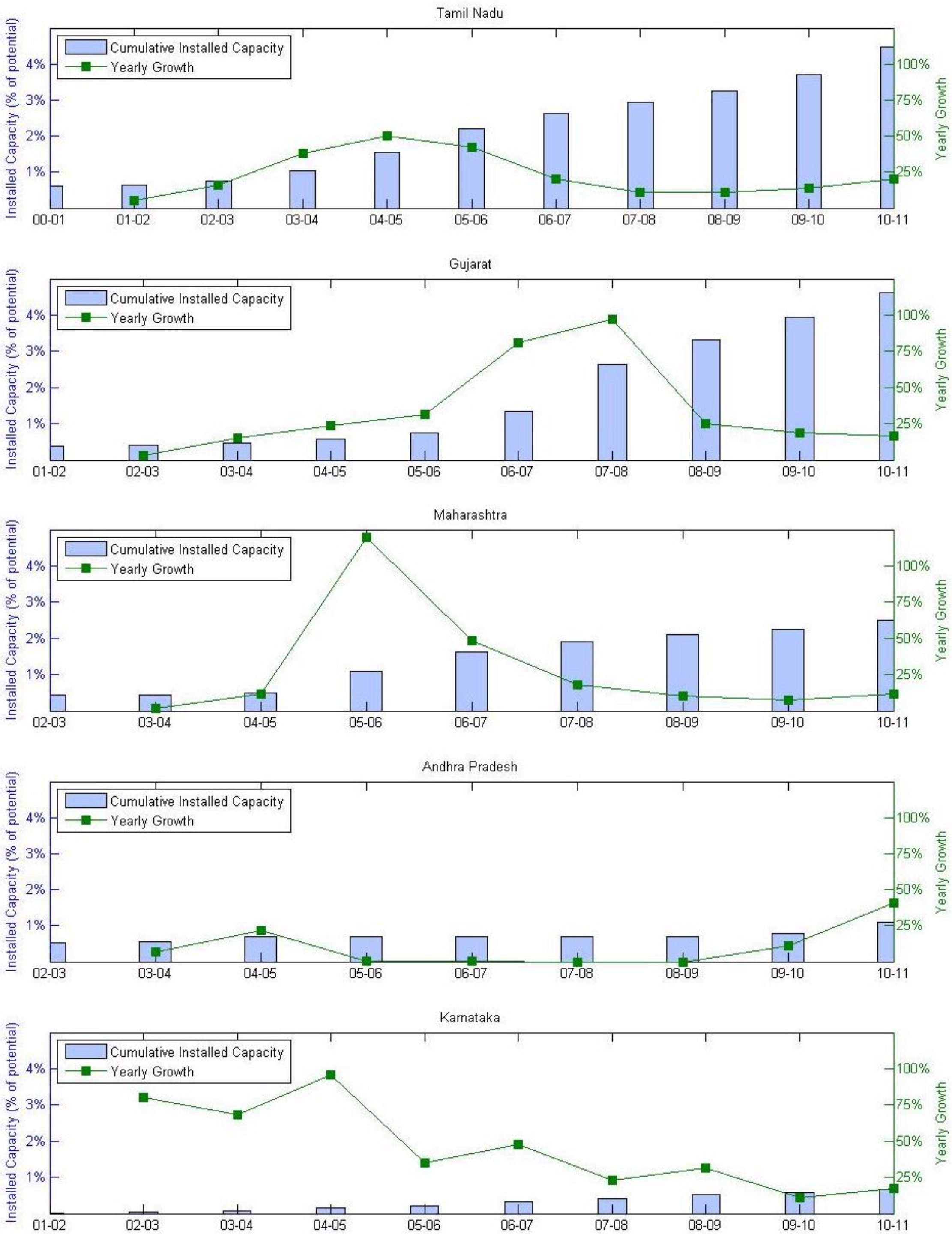

Figure 15. Installed wind capacity and yearly growth for later period of diffusion.

Table 9: Strategies covered by state government initiatives in the later phase of diffusion.

		Tamil Nadu	*Gujarat*	*Maharashtra*	*Andhra Pradesh*
Barrier	Technical			X	X
	Financial			X	
	Regulatory	X	X	X	X
Actor	R& D			X	X
	Systems and Infrastructure	X		X	
	Knowledge and Learning		X	X	X
Environment	Institutional Change	X	X	X	X
	Market Creation			XX	X
	Advocacy coalitions				
Direct/ Indirect	Direct		X	XX	XX
	Indirect	X		X	
Supply/Demand	Supply		X	XXX	XX
	Demand	X			

Tamil Nadu continued to lead wind power development during the later phase of diffusion, remaining the state with the highest percentage of potential achieved until around 2008. It experienced peak growth in 2004-2005 of 50.12% after the state started granting permission for wind developers to set up captive generation plants using wind power.[9] Although Gujarat enjoyed early success in the initial phase of diffusion, its growth stagnated around the turn of the century. This can be attributed to inconsistent or absent state policies regarding wind power during this time (Rao and Kishore, 2009). In 2007, however, the state introduced a comprehensive wind energy policy, followed by 81% growth in 2006-2007 and the 97% growth

[9] Captive power plants are electricity generation plants set up by individuals or co-operative associations for use primarily for the individual or members of the association.

in 2007-2008. Shortly thereafter, it surpassed Tamil Nadu as the state which reached the highest percentage of its wind power potential in 2008-2009.

Between the two states, differences in the strategic structure of their initiatives occur in three categories: empowered actor, direct versus indirect, and supply versus demand. While Tamil Nadu's allowance of captive generation strengthened the overall system in which wind energy operates, provided indirect support and acted on the demand side, Gujarat's comprehensive wind energy policy strengthened ties between different members of the wind diffusion community, directly applied to wind power and acted on the supply side. The higher growth values found in Gujarat's wind power sector are consistent with a previous study which found that policies promoting mutual knowledge and learning are more effective (Fernandez de Lucio et al., 2010). They also suggest that direct initiatives acting on the supply side make a larger impact in diffusion. The lack of demand side measure used by the states in totality support the importance of acting on the supply side and reducing initial barriers to adoption of wind infrastructure. However, as systemic innovations, wind energy generators cannot act on their own, but require substations, transmission lines and distributions networks for electricity to reach users. Therefore while direct incentives may be more effective now, as wind technology continues to mature and become financially competitive with incumbent energy sources, we should expect more emphasis on addressing the challenges of providing proper support infrastructure. In fact, several of the experts and academics interviewed predict that India's already strained electricity grid will be the next major bottleneck in the diffusion of renewable energy sources.

In 2004, Maharashtra completed its last wave of demonstration projects, introduced a renewable energy policy, and also created a "green energy fund" that supplied capital for supporting infrastructure such as transmission lines and access roads. Combined, these three initiatives covered a wide variety of strategies as evident in Table 9, including all barriers, empowered actors, two out of the three enabling environments, and addressed both wind technology as well as its support infrastructure. It is difficult to ignore their contribution to the 120% growth in installed capacity in 2005-2006 followed by 48% growth in 2006-2007. In fact, Maharashtra had the highest growth percentage of a single year out of all states during the later diffusion phase. This further reinforces the notion that a comprehensive incentive package covering multiple strategic areas is necessary to impact diffusion, a trend observed during analysis of the first phase of diffusion.

Andhra Pradesh finished its last demonstration project in 2004 and experienced 21.93% growth in 2004-2005. However, over the next several years, increases to installed capacity of wind infrastructure for the state are negligible. Only after it introduced a renewable energy policy in 2008 did diffusion pick up again, with the most recent percentage growth in 2010-2011 measuring 40.72%. This finding may seem to contradict evidence that a comprehensive strategy profile from multiple incentives spurs diffusion, since completion of the demonstration projects combined with central and state government incentives from the initial period of diffusion cover almost all strategies represented by the strategic structure matrix, yet almost no new capacity was added in the following years. However, past studies have emphasized the feedback loop and virtuous cycle present in diffusion (Jacobsson and Lauber, 2006). For example, as technology matures and financial barriers are overcome, new regulatory issues may arise that need to be addressed. This can be observed by comparing Maharashtra’s diffusion trajectory with that of Andhra Pradesh, since both states had similar initial approaches to wind energy development.

Figure 16 isolates the diffusion curves of the two states and annotates the time of regulatory initiatives.

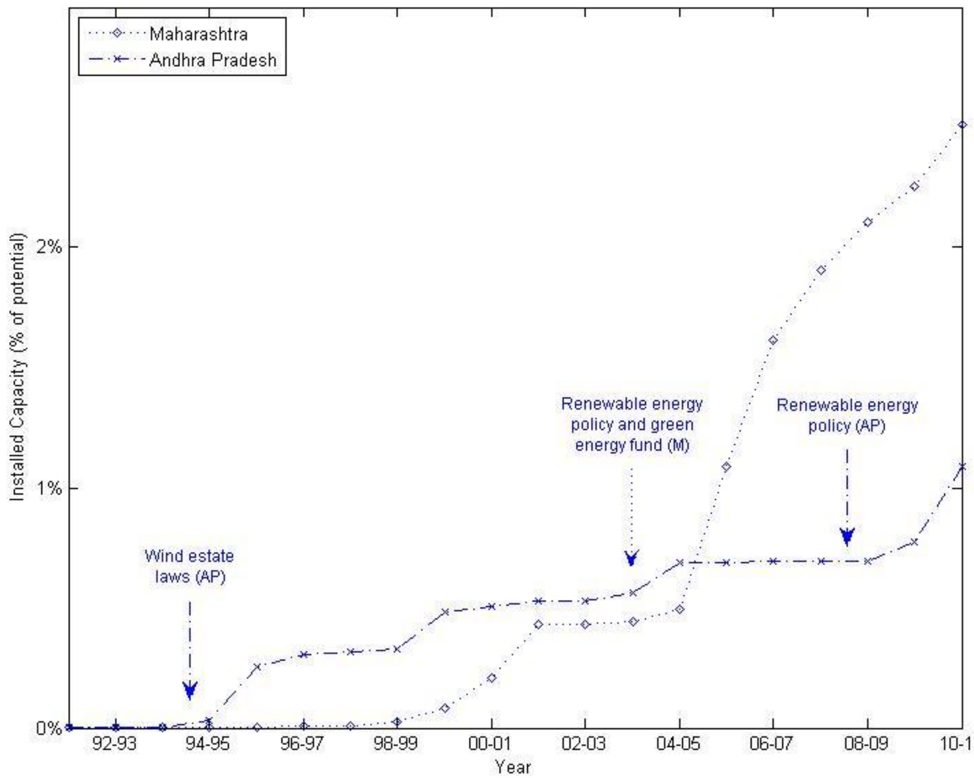

Figure 16. Installed wind capacity for Maharashtra (M) and Andhra Pradesh (AP).

Both had state nodal agencies established in 1986 and demonstration projects that spanned from 1994 to 2004. However, while Andhra Pradesh experienced growth levels comparable to Gujarat's in terms of percentage of wind potential starting around 1995, Maharashtra's wind energy market did not take off in a similar fashion. This discrepancy can be explained by Maharashtra's lack of additional measures to overcome regulatory barriers, while Andhra Pradesh had wind estate laws which helped small developers acquire land for wind farms starting in the mid-nineties, echoing a broader change in land allotment policies for wind power (Jagadeesh, 2000). In the later phase of diffusion, the trend is reversed, with Andhra Pradesh's growth stagnating and Maharashtra's development increasing and eventually outpacing Andhra Pradesh's starting around 2005. The timing correlates with efforts by Maharashtra to introduce a comprehensive renewable energy policy, including a green energy fund, as discussed earlier. Predictably, diffusion increased after the government of Andhra Pradesh introduced their own renewable energy policy in 2008.

Because Karnataka had experienced so little growth at the start of its later phase in 2001-2002, a small addition to installed capacity constituted a large percentage, so the high numbers in the early years are quite misleading. In fact, an argument could be made that Karnataka is just finishing its initial period of diffusion relative to the other states. Its lateness in establishing a state nodal agency and starting its demonstration projects puts it about ten years behind. If we compare Karnataka's installed capacity values and initiatives from 2002-2010 to Tamil Nadu's from 1992-2000, we find the two states have very similar diffusion curves as well as strategic structures defined using the matrix. These findings provide internal validation that increases in installed capacity can be attributed to superstructure organization strategies and that the strategic structure matrix is an appropriate tool to analyze the relationship between initiatives and increased diffusion.

CONTRIBUTIONS, LIMITATIONS AND FUTURE RESEARCH

The case study on wind energy in India provides some important insights into the effect of the strategic structure of initiatives used to promote diffusion of renewable energy technologies. By linking the timing of initiatives used with increased growth in the diffusion curve, we provide evidence that differences in the strategic structure can help explain the variations in path and pace of diffusion for the five states studied. By creating and using the strategic structure matrix as the framework for our analysis, we gain a deeper understanding into the nuances of strategies for diffusion and how they relate to one another. Additionally, our findings carry important policy implications for superstructure organizations within the innovation diffusion community and how they design incentives to speed up adoption of new technologies.

Theoretical contributions

We introduce a new framework—the strategic structure matrix—to improve upon past analysis of the relationship between organizations and innovation diffusion. Focusing our attention on superstructure organizations, defined by Lynn et al. (1996) as those that coordinate the flow of information and activities in an innovation community, we narrow our attention to the strategies used by organizations to promote diffusion. After reviewing past literature, we identified five main categories of strategies to describe an initiative: lowering a diffusion barrier, empowering an actor type, enabling an environment necessary for diffusion, targeting the technology or its support infrastructure, and acting on the demand or supply side. We used these categories to shape the strategic structure matrix in order to form a strategic profile of each initiative, composed of one strategy from each category. In providing a five-dimensional strategic structure instead a one-dimensional analysis as used in previous studies, we improved understanding of initiatives used to promote diffusion and provided guidance on how to better understand and develop effective policy measures to encourage use of renewable energy technologies.

In order to test the applicability of the matrix, we performed a case study on the diffusion of wind energy infrastructure in the five Indian states of Tamil Nadu, Gujarat, Maharashtra, Andhra Pradesh, and Karnataka. We found that framing initiatives in terms of their strategic structure helped successfully explain why some states were in a better position to take advantage of Central Government incentives in the early 1990s. Additionally, it was also able to identify reasons for continued growth of some states and not others in the later phase of diffusion. A noteworthy finding from this study is that the most successful states have a set of initiatives that cover almost all strategies within a category in the strategic structure. It also suggests that the effect of additional policy measures is dependent on the current incentive landscape for development of wind energy, and therefore targeting gaps in a state's strategic structure may be most fruitful. For example, if several initiatives empower actors working to bolster R&D and support surrounding systems and infrastructure, but fail to include actors involved in knowledge sharing and mutual learning, then additional initiatives should address the missed strategic focus.

Implications for policy

Taken as a whole, the case study suggests that regulatory measures are more effective when enacted on a local level and supply-side measures are overwhelming favored. In India, the states have a large amount of autonomy when it comes to electricity. Thus, every state has unique regulatory challenges when it comes to increasing its capacity for wind energy depending on the existing laws and infrastructure. For example, the wind estate laws used in Andhra Pradesh would have had little impact in Tamil Nadu where liberal land policies already existed and much of the land used for wind power is private. Logically, regulatory measures should be considered by each state independently, an approach supported by a Central Government order for state governments to set up nodal agencies with their own rules and regulations for wind energy in 1995 (Jagadeesh, 2000). The importance of a local regulatory measure is further illustrated during the comparison of Maharashtra and Andhra Pradesh and in Figure 16. Interestingly, the states often enact the same type of regulatory measure, such as creating a nodal agency for renewable energy, which all of them eventually did. While Tamil Nadu was the only state without a renewable energy policy at the completion of the case study, interviews with officials at TEDA indicate a policy is forthcoming.

The importance of regional regulatory measures extends beyond the five Indian states studied. Financial and technical aspects of an innovation are more likely to remain constant over wider physical boundaries than the regulations associated with adoption. Although the fact that demonstration projects built in one state did not translate into broader adoption of wind power in neighboring states may suggest the technical aspect varies more than expected across geographical locations. Financial incentives seem best suited to be used on a broader geographical scope. The early initiatives by the Central Government to increase wind energy development were all financial in nature, and were most successful in states which had already addressed to some extent the technical and regulatory hurdles to diffusion. This finding provides insight to national governments and global alliances tasked with increasing renewable energy production and decreasing dependence on conventional fuel sources. For example, the United States debated instituting a national renewable portfolio system (RPS) to synchronize the variety in program design of many state RPS plans of the states that had an RPS, including a provision that 20% of the nation’s electricity come from renewable sources. It ultimately failed to pass. In light of this study, perhaps it was best to have left alone the states’ individual compliance percentages of how much electricity comes from renewable sources, since it is a regulatory measure. However, the credit trading markets associated with the RPS program may be more effective if they were national in nature, since the ability to sell renewable energy credits (RECs) overcomes the financial burden of developing renewable energy. This arrangement was used by the nations who ratified the Kyoto protocol which aimed to decrease global levels of carbon emissions. In Europe, for example, each country had its own target decrease in emissions, but compliance certificates were traded between countries on the European Climate Exchange.

Like most energy technology, wind systems require substantial upfront investment and have a long payback period. Although technological advances continue to decrease wind power production costs, it is still more expensive than coal- or gas-based generation in all of the five Indian states studied (Sargsyan et al., 2010). Initiatives that act on the supply side decrease the initial barriers to diffusion, financial or otherwise, and were overwhelming favored by the states and Central Government. It should be noted, however, that the ability to depreciate 100% of wind assets in their first year acted on the demand side since benefits could not be received until after installation, and was cited as a major reason for increased capacity in the early to mid-1990s before the introduction of the MAT. A possible reason is that all the benefits are received almost immediately after installing new capacity, drastically decreasing the payback period in a similar way that supply-side measures do.

Limitations and future research

Although some important contributions have been made, some limitations to the proposed approach still exist. While less simplified than previous studies, the strategic structure matrix is still a simplification of a complex diffusion process with many inter-related superstructure and substructure organizations. Additionally, the case study does not provide enough data to do any statistical analysis to increase robustness of the findings shared above. Similarly, it cannot provide a comparative evaluation of the relative importance of one strategy or category over the others. Continued research to quantitatively evaluate the effectiveness of certain strategies, for example, if a positive influence in one area may be canceled out by another, or if existence of one strategy is a necessary precursor for diffusion, will lead to a better understanding of the impact of initiatives. A broader perspective of the interactions of initiatives with one another and the larger power sector would also complement the analysis presented here. The links between wind energy diffusion and the growing numbers of actors in the power sector are not fully explored in this paper. The regional and global factors which affect investment interests in infrastructure in general and technological advancements will also shape the reaction of renewable energy investors. Additional research aimed to incorporate the strategic structure matrix into larger diffusion models can provide deeper insights into effective and efficient development of renewable energy. Nevertheless, our study is valuable as a first effort in demonstrating the use of the strategic structure matrix.

Future research can address some of these limitations and advance understanding of strategic profiles used to impact diffusion. Superstructure organizations continue to play an important role as the wind energy sector grows in India. For example, in December 2009, the Ministry of New and Renewable Energy started offering developers a choice between accelerated depreciation or a generation-based incentive of Rs 0.5 per kWh of electricity produced using wind energy. The authors chose not to include this incentive in the case study as not enough time has passed to evaluate its popularity or effect. However, future research can update diffusion curves and the strategic structure matrix started in this paper with additional data in order to provide more robust insights into how to shape future policies aimed at promoting diffusion. Additionally, similar case studies can be done in other geographical locations or on different types of innovations. Our case study dealt exclusively with governments which have a higher basis of authority than other superstructure organizations. Analysis of other types of superstructure organizations may provide different insights on the relative importance of individual and combinations of strategies. Additional studies can further refine and validate the strategic structure matrix.

While this paper took a diffusion-centric approach to strategies used by organizations, Lynn et al.'s (1996) original innovation community framework borrowed heavily from organizational ecology theory. An in-depth study of strategies from that perspective could complement the findings presented here, especially as a way to include the external factors of a larger regulatory environment. Although the five states studied are comparable in many ways, including geographical size, population, and percentage of urban and rural residents, there are still institutional differences between them that were not captured during the case study, but may influence how incentives for wind energy growth are created and received. A closer look at the relationships of the superstructure organizations with one another and the larger diffusion community is necessary. By doing so, the research community is able to not only shape future policy to increase renewable energy development, but can more broadly provide a deeper understanding of the impact of organizations on diffusion.

CONCLUSION

In an attempt to tackle the broader issue of how superstructure organizations can effectively impact diffusion, we introduce the literature-derived strategic structure matrix as a novel new framework to analyze the relationship between strategies and future diffusion. Developed from a theoretical background rooted in research on the role of organizations in the diffusion process, the strategic structure matrix improves classification and comparison of the strategic focus of initiatives used by superstructure organizations. We validate the use of the matrix by performing a case study on wind power in five states in India. The analysis suggests the importance of a comprehensive strategic profile, regional regulatory measures, and supply-side measures. The findings from this paper can shape future policy formation in order to increase diffusion of renewable energy.

Additionally, the strategic structure matrix adds to existing literature on how superstructure organizations impact diffusion within an innovation community. By bringing together disparate studies on the topic and providing a framework with which to analyze strategies in a more comprehensive way, we hope to shape the direction of research on the diffusion of renewable energy technologies while at the same time impacting more general research at the intersection of organizations and diffusion.

Chapter 4

RENEWABLE ENERGY INVESTMENT IN EMERGING MARKETS: THE USE OF AGENT-BASED SIMULATION TO EVALUATE IMPROVEMENTS TO THE CLEAN DEVELOPMENT MECHANISM[10]

ABSTRACT

Over the next two decades, 80 percent of increased electricity demand will come from emerging markets. Renewable energy has the opportunity to play a prominent role in meeting this demand. In the past, industrialized countries have invested in or financed numerous renewable energy projects in developing countries, primarily through the Clean Development Mechanism (CDM) of the Kyoto Protocol. However, critics have pointed to its bureaucratic structure, problems with additionality and distorted credit prices as ill-equipped to streamline renewable energy investment. Although suggestions to alleviate these shortcomings have been offered by academics and industry professionals, we lack a quantitative evaluation of policy improvements. In this paper, we use an agent-based model to simulate the impact of policy on investment decisions. Specifically, we modeled individual firm behavior in evaluating whether or not to invest in wind energy infrastructure in India, Brazil and China, with the total amount of investment derived by aggregating firm decisions over time. Data from 2578 past projects as well as literature on investor behavior is used to inform the model structure and parameters. Simulations are performed under various policy scenarios for each country. Our results show that

[10] This paper was co-authored with Professor John E. Taylor.

the CDM acts differently in each country and support research encouraging country- specific policies. They also reveal that while streamlining the approval process and reconsidering additionality can lead to non-trivial increase in total investment, stabilizing policy and decreasing investment risk will do the most to spur investment. These findings will aid policy makers in future policy designs to encourage renewable energy development in emerging markets.

INTRODUCTION

Over the next two decades, developing countries will account for 80 percent of increased electricity demand worldwide. Renewable energy is expected to play a large role in meeting this demand. However, development of renewable energy infrastructure has been hindered by lack of financing and difficulty attracting capital (Gupta, 2012; Liming, 2009; Masini and Menichetti, 2012). The high risk perception leads to a higher cost of capital (Donovan and Nunez, 2012; Sadorsky, 2012), and in developing countries, other social priorities act as competition for scarce funds (Gupta, 2012). Many countries also experience a “carbon lock-in” of incumbent energy sources, with existing infrastructure unable to adapt beyond fossil-fuel based resources (Unruh and Carrillo-Hermosilla, 2006).

In the past, industrialized countries have provided much of the investment and financing to develop renewable energy in emerging markets. This was due in part to the Clean Development Mechanism (CDM), a flexibility mechanism defined in the Kyoto Protocol aimed to reduce overall global greenhouse gas emissions by providing financial incentives for using zero or low-emitting technologies. Although many projects have been realized through the CDM, academics and industry professionals alike have deemed it inefficient and bureaucratic. Since the renewable energy industry is highly influenced by regulatory drivers as compared to other industries (Burer and Wustenhagen, 2009; Gupta, 2012; Unruh and Carrillo-Hermosilla, 2006), it is especially important that policies encouraging renewable energy development are well-designed and effective. Given that future financing for renewable energy in developing countries will likely come from developed countries (Donovan and Nunez, 2012), the research community needs to evaluate the CDM as a tool to encourage such investment.

In this paper, we evaluate the impact of potential improvements to the CDM on investment using agent-based simulation techniques. We focus our analysis on the level of wind energy investment in India, Brazil and China under three different policy improvements. The next section provides details of the CDM including its most common criticisms and suggested improvements, as well as policy backgrounds for the three countries studied. This is followed by an introduction to agent-based simulation and details of our model. We then share our results and analysis before concluding with policy recommendations and a discussion of opportunities for future research.

KYOTO PROTOCOL AND THE CLEAN DEVELOPMENT MECHANISM

Program description

The Kyoto Protocol is a binding pledge adopted by several industrialized (“Annex I”) countries to reduce greenhouse gas emissions, in part by using zero- or low-emitting technologies for electricity production. Emission reduction is awarded with certificates that can be traded between countries, a system intended to reduce emissions in the most cost effective manner. The CDM is a flexibility mechanism defined in the Kyoto Protocol that allows projects in developing countries with no binding commitments to qualify for emission avoidance certificates, also known as Certified Emission Reduction (CER) certificates. The certificates are issued based on a baseline emission scenario and the avoided emission attributed to development of renewable energy projects. CERs can be used by Annex I countries to meet part of their binding commitments.

In theory, the CDM should encourage bi-lateral development of renewable energy projects in developing countries, in which an industrialized country's investment in a project is repaid in part by CERs. Recently, unilateral projects developed solely by the non-Annex I host country have also emerged, with the CERs sold via various exchanges to a country looking to meet its own binding target. As of 1 April 2013, 6660 projects have been registered worldwide with 2337 projects under review. The CDM is one of the primary ways in which developed countries subsidize renewable energy infrastructure in developing countries (Donovan and Nunez, 2012; Hultman et al., 2012; Lewis, 2010).

Key criticisms of the Clean Development Mechanism

Despite its apparent success, the CDM has been widely criticized, leading some researchers to suggest that it be abandoned in favor of fiscal regulation specific to individual countries alongside binding emission reduction goals (Lewis, 2010; Zavodov, 2012). Other academics believe correcting some key flaws will greatly enhance the CDM's effectiveness. Three main issues examined here are its bureaucratic process, the effectiveness of "additionality," and distorted credit prices due to uncertainty around credit supply.

Bureaucratic process

Each renewable energy project must apply for CDM status in order to receive CER credits through a lengthy, "unwieldy and opaque bureaucratic structure" (Hultman et al., 2012, pg. 91). The Samana wind farm in Gujarat, India, for example, was commissioned in 2009 and did not receive CDM status until February 2013. Project developers rank the risk of non-approval as a primary concern when developing renewable energy in emerging markets (Hultman et al., 2012). The high transaction costs of participating in the program, therefore, reduce its benefits. Lewis (2010) and Dechezlepretre et al. (2008) suggest that streamlining the approval process as well as approving a program with multiple projects would greatly strengthen the design of the CDM.

Additionality

For a project to receive CDM approval, it must meet the “additionality” criteria, which requires developers to show that the project could not have been built without the additional revenue stream from sale of CER credits. However, these calculations of financial feasibility are based on self-reported rates of return of developers (Donovan and Nunez, 2012; Unruh and Carrillo-Hermosilla, 2006) and there is no standard or uniform way through which this is done. Evidence from China (Lewis, 2010), Brazil and India (Hultman et al., 2012) imply some projects receiving CDM approval were not “additional.”

Distorted credit prices

Lastly, critics have cited distorted CER credit prices as a major drawback of the CDM. Aside from the market reactions to the recent global recession and European debt crisis, the particularities of the CDM have led to irrational market fluctuation of credit prices. Because of the lengthy and oftentimes opaque approval process, there is uncertainty around the number of credits that will be available on the market in the future, clouding price-change signals (Zavodov, 2012). Additionally, because the number of credits issued for a project is relative to a theoretical business-as-usual baseline, credits earned for identical projects in different locations will vary (Hultman et al., 2012), adding to the uncertainty around credit supply. The future of the CDM is also undetermined, since countries have yet to renew their reduction commitments. This increases risks for developers, raising the required rate of return to participate in renewable energy projects for some investors and possibly deterring others. Stabilization of policy with greater certainty in future credit supply could increase investor confidence and lead to additional investments.

Need for quantitative analyses of Clean Development Mechanism improvements

In short, the CDM in its current state is ill-equipped to streamline renewable energy investment in emerging markets (Zavodov, 2012). Although suggestions have been made to improve the CDM, no research has quantitatively evaluated the effect of these changes on total investment in renewable energy infrastructure. Informing policy makers of which changes can bring about the greatest increase in investment is valuable in designing future policy and continuing to encourage renewable energy investment in emerging markets. As a step in this direction, we use agent-based simulation to measure the total investment in wind energy infrastructure in India, Brazil and China under improvements to the CDM.

Key participants of the Clean Development Mechanism

India, Brazil and China are among the top countries in terms of CDM participation. According to the UNEP Risø Centre, China and India are the most active countries in Asia making up 55.0 percent and 29.7 percent, respectively, of all Asian CDM projects. Brazil leads with 35 percent of all Latin American CDM projects. Specifically for wind power, China, India and Brazil have the most installed capacity of wind energy infrastructure out of all countries eligible to participate in the CDM as of 2012 (GWEC, 2012b). Additionally, all three countries are in the top ten countries with the most installed capacity during 2012 (GWEC, 2012b). However, each country's potential wind resource is still much greater than the existing infrastructure, as shown in Table 10, and will continue to increase as turbine technology advances.

Table 10. Wind power potential and installed capacity in India, Brazil and China.

	Potential	**Installed Capacity in 2012**[1] ***(% of potential)***
India	102 GW[1]	18.4 GW *(18.0%)*
Brazil	350 GW[1]	2.5 GW *(0.71%)*
China	2380 GW[2,3]	75.3 GW *(3.16%)*

[1] GWEC, 2012b.
[2] Phadke, 2011.
[3] Jiang et al., 2011.

The above facts show that India, Brazil and China are important players in the CDM program with a rich dataset of projects to study, and continue to be leaders in the growing global wind industry. Below are brief descriptions of the wind development and regulatory landscape in each country.

India

In 1983, the Wind Energy Program was started by the Ministry of Non-conventional Energy Sources (MNES) (currently the Ministry of New and Renewable Energy (MNRE)) and had broad goals of assessing wind resources, building demonstration projects and creating industry-utility partnerships (Bhattacharya and Jana, 2009; Pillai and Banerjee, 2009; Rajsekhar et al., 1999). Although an initial leader in the wind energy industry compared to other developing countries, India's lack of an integrated energy framework and a national mission dedicated to wind has stunted its growth and allowed countries such as China to soar past its progress (GWEC, 2012b). Despite this, several incentives have helped wind energy grow considerably over the past two decades, and India currently ranks fifth in installed capacity worldwide. At the national level, a bundle of tax incentives, including accelerated depreciation, low tariffs on imported wind energy technology and reduced or exempt tax for income from power sales helped developers largely using balance sheet financing (as opposed to project financing). Additionally, the Indian Renewable Energy Development Agency (IREDA) was established in 1987 to provide financing to developers. It instilled confidence in the economic viability of wind power and paved the way for private banks to lend to developers. Several state governments have enacted preferential feed-in tariffs, which encourage wind power development by providing a higher rate to electricity produced from wind. Recently, some states have also implemented renewable purchase obligations (RPO) which require a certain amount of power produced to come from renewable sources, although lack of enforcement have negated much of its intended effect. Looking forward, some challenges facing the wind industry in India include implementing an integrated framework and a national feed-in tariff program, as well as continued development of transmission and other support infrastructure.

Brazil

Brazil has long been a leader in renewable energy due to its numerous hydroelectric power plants. In an effort to diversify its energy portfolio and to hedge against low power production during the dry season and droughts, Brazil has aggressively promoted wind as part of its primary energy mix. Although a recent entrant into the wind power industry, the country is characterized by strong winds that allow turbines to operate for a longer period of time than in most other countries, giving the technology operational and financial advantages. In 2002, the government created the Program for Incentive of Alternative Electric Energy Sources (Proinfa), which consolidated several previous actions promoting alternative energy development and provides subsidies and financial incentives funded through an electricity surcharge on power consumers (Dutra and Szklo, 2008). The National Development Bank also provides financing for machinery and equipment through its subsidiary Finame. It has created a strong domestic industry and eleven international equipment manufacturers have opened production facilities in the country (GWEC, 2012b). Starting in 2009, the government has held several wind-only energy auctions, essentially guaranteeing that wind energy operators received over half of the contracts to sell power in 2011 and 2012 (Leahy, 2013). However, the prices at which developers have agreed to sell electricity are extremely low and have caused concerns over the sustainability of future wind power growth (Leahy, 2013). In order to continue growth of its wind industry in the upcoming years, Brazil must ensure sufficient transmission infrastructure to keep up with the increase in electricity production and reduce financial risks through improved government regulations (GWEC, 2012b; Martins and Pereira, 2011).

China

Over the past decade, China has experienced rapid growth and currently has the highest installed capacity of wind energy infrastructure globally. In 2005, the government created the Renewable Energy Law of the People's Republic of China. After its adoption, a series of policies have been enacted to promote renewable energy development, including a dedicated renewable energy development fund supported by an electricity surcharge on consumers (Jiang et al., 2011). Additionally, feed-in tariffs have been used to give wind power a financial advantage. The manufacturing industry has also flourished due to policy incentives, creating a full supply chain with 88 percent of the domestic market occupied by Chinese manufacturers (Jiang et al., 2011). Since most developers are stated-owned enterprises supported by government-backed commercial banks eager to invest in infrastructure, the wind industry in China experiences lower financial risks and was largely unaffected by the 2009 crisis that upset the US and European industries (GWEC, 2012b). Several obstacles still remain, however, most notably the inadequate transmission system and lack of regulations for wind power integration into the grid (GWEC, 2012b; Jiang et al., 2011).

Opportunities created by India, Brazil and China analyses

By analyzing these three countries, not only can we gain insight into which improvements to the CDM are the best at encouraging development, but under what circumstances. By doing so quantitatively, we aim to measure the effect improvements to the CDM policy will have on investment decisions. Our results will better inform policy makers as to where they should concentrate their efforts to create the greatest increase in total renewable energy investment in emerging markets.

AGENT-BASED SIMULATION

In order to determine the impact of changes to the CDM, we built an agent-based model to simulate the total investment in renewable energy given certain policy environments. Agent-based simulation was selected because of its extensive use in past studies to model and evaluate investment decisions under various policy scenarios. Mueller and de Haan et al. (2009), de Haan et al. (2009) and Eppstein et al. (2011) used agent-based simulation to determine how much incentives affect car purchase decisions and market penetration of plug-in hybrid electric vehicles. Jackson (2010) analyzed energy efficiency of a smart grid program and Veit et al. (2009) determined the implications of transmission constraints on the German electricity market, both using agent based simulation.

Our agent-based model simulated investment decisions of an individual or firm seeking to develop a wind energy project. The decision is based on several factors that influence a project's potential revenue and profitability, including project properties, local conditions, and an investor's own characteristics. The model aggregated all investment decisions of investors over time to determine the total investment. Simulations were performed for investors in India, Brazil and China, allowing us to quantify the incremental investment on wind energy infrastructure under the presence of the CDM in each country. Sensitivity analysis was done to measure the impact of three improvements to the CDM program: streamlining the approval process, reconsidering the requirement of additionality, and reducing investor risk by stabilizing policy. The results allowed us to compare the effectiveness of the CDM and various program changes within and across countries.

Model structure and baseline calibration

The agent-based model was designed and coded in AnyLogic, a powerful and robust simulation environment. The simulation environment is populated with agents representing individuals or firms, which we call "investors." An investor decides whether or not to build a wind energy project by evaluating its profitability. The decision process is represented in Figure

17. By default, the simulation initially treats all investors as “inexperienced.” Each year, an investor considers developing a project with the properties and situational characteristics presented in Table 11 and detailed later in this section. The investor calculates the project’s net present value (NPV) using its required rate of return. If the NPV is positive, then the project is built and the investor becomes “experienced.” The rates of return used for experienced and inexperienced investors are based on a study done by Donovan and Nunez (2012) on the cost of capital for renewable energy projects in emerging markets, and are also listed in Table 11. If an experienced investor does not build any projects for five years, then it reverts back to inexperienced. We ran the simulation for a period of *T* years and aggregated the costs of built projects to determine the total investment.

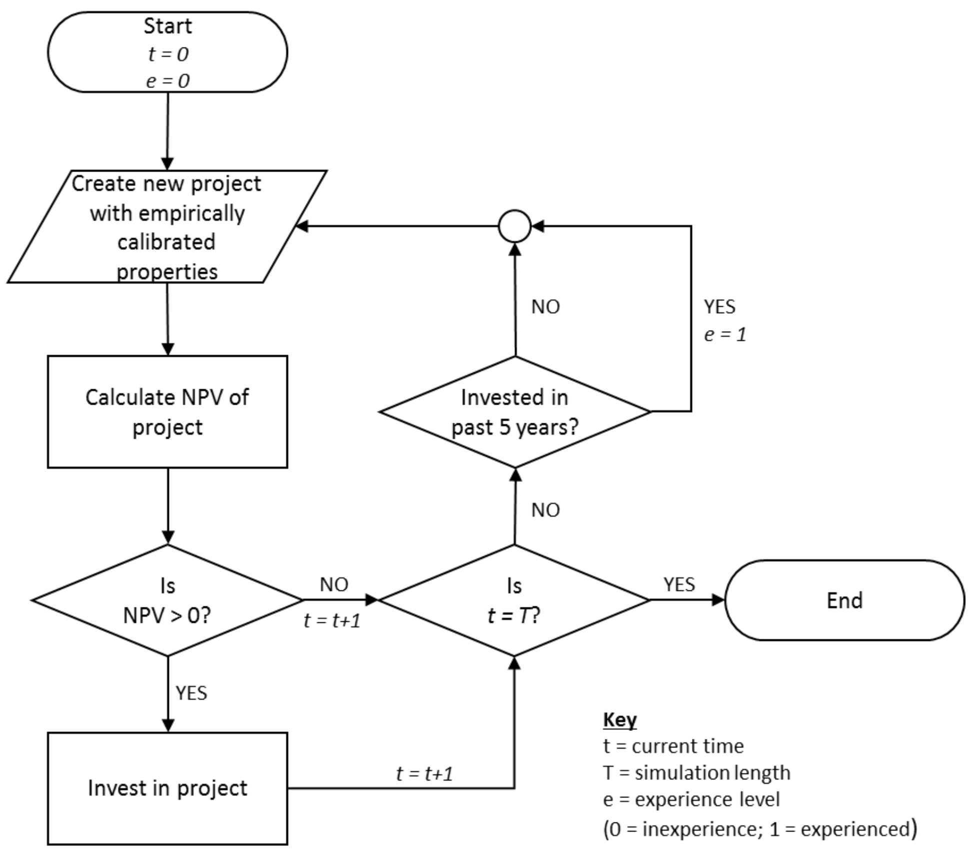

Figure 17. Decision process of an investor.

Table 11. Parameters used in baseline agent-based simulation.

	Parameter	*India*	*Brazil*	*China*
Environment	Number of investors	50	50	50
	Delay in receiving credits*	3 years	2 years	2 years
	Probability of getting CDM approval*	80.57%	77.5%	97.91%
Investor	Experienced investor discount rate**	19.06%	13.68%	11.08%
	Inexperienced investor discount rate**	14.80%	12.09%	8.32%
	Time of inactivity to revert back to inexperienced	5 years	5 years	5 years
Project	Years credits are received*	10 years	7 years	7 years
	Years electricity is produced	20 years	20 years	20 years
	Project size*	Exponential distribution with mean = 17.02 MW	Exponential distribution with mean = 75.13 MW	Either 50 MW or 200 MW
	Capacity factor*	23.3%	42.7%	24.5%
	Average CER credit received per MW capacity*	N(1891, 298)	N(1259, 409)	N(2032, 304)
	Average project cost per MW capacity*	N(1229013, 237711) USD	N(1971742, 682573) USD	N(1289005, 160466) USD
	Yearly O&M cost per MWh electricity produced***	10 USD	10 USD	10 USD

* Derived from CDM project database
** Donovan and Nunez, 2012.
*** International Renewable Energy Agency, 2012.

The cost and revenue streams for a project are based on four components: a) initial cost, b) yearly revenue from electricity sales, c) yearly operations and maintenance cost, and d) yearly revenue from Certified Emission Reduction (CER) credit sales. The NPV for each project is calculated using the following equation,

$$NPV = -\text{initial cost} + PV(\text{electricity revenue}) - PV(\text{O \& M costs}) + PV(\text{credit revenue})$$

with PV representing the present value calculation of revenue or cost streams.

While the structure of the model remained the same for all three countries analyzed, model parameters necessary to calculate costs and revenue were derived for each country using a database of all projects that have applied for CDM registration as of 1 April 2013, publicly available from the UNEP Risø Centre. After streamlining the data to focus on wind energy and removing duplicate projects that were listed more than once because of resubmissions, 83 projects were used to calibrate parameters for Brazil's model, 1544 for China's, and 931 for India's.

The initial cost of a project was calculated by multiplying the project size in megawatts (MW) of installed capacity by the average cost per MW. For each country, project size was randomly simulated based on an empirically-determined distribution of past projects. In the models for both India and Brazil, an exponential distribution with positive skewness (long right tail) was observed for project size with a mean of 17.02 MW and 75.13 MW, respectively. In China, the majority of CDM wind energy projects were between 40 and 50 MW, with an astonishing 999 (64.7%) projects with the exact size of 49.5 MW. This is because projects larger than 50 MW require approval from the National Development and Reform Commission (NDRC) while smaller projects are approved by local provincial governments and recorded with central government authorities (Jiang et al., 2011), suggesting that developers prefer working with local authorities. Therefore in China's model, a project's size was simulated as either 50 MW with a probability of 0.9 or 200 MW with probability 0.1 in order to include the larger scale projects. The average unit cost per MW was also determined from information in the database. Project cost in all three countries followed a normal distribution, with no significant correlation found between project size and unit cost.

Yearly revenue from electricity sales was forecasted by multiplying the yearly electricity production by the expected price of electricity. It was received for the lifecycle of the project, which is 20 years. Yearly electricity production was calculated using capacity factors derived from the CDM project database for each country. The expected price of electricity was determined using feed-in tariff data for wind power in India (GWEC, 2012a) and China (Jiang et al., 2011). To maintain flexibility in the model, the feed-in tariffs for each Indian state were averaged and applied uniformly to all projects in India. Similarly for China, feed-in tariffs for individual zones were also averaged. A breakdown of the feed-in tariffs for each state and the average tariff utilized in our model is provided in Table 12 and Table 13. Brazil does not currently utilize feed-in tariffs for wind energy. Instead, the average price of the 2011 wind power auction of 99.58 BRL per MWh as reported by Bloomberg News and Merco Press was used to inform the model.

Table 12. Feed-in tariffs for electricity produced from wind power in China.

	Feed-in tariff per kWh [CNY]
Category 1	0.51
Category 2	0.54
Category 3	0.58
Category 4	0.61
Average	***0.56****

Source: Jiang et al., 2011.
*Converted to USD using average monthly exchange rate for 2011 of 1 USD = 6.464 CNY.

Table 13. Feed-in tariffs for electricity produced from wind power in India.

	Feed-in tariff per kWh [INR]
Andhra Pradesh	4.70
Gujarat	4.23
Haryana	Wind Zone 1 - 6.14
	Wind Zone 2 - 4.91
	Wind Zone 3 - 4.09
	Wind Zone 4 - 3.84
Karnataka	3.70
Kerala	3.64
Madhya Pradesh	4.35
Maharashtra	Wind Zone 1 - 5.67
	Wind Zone 2 - 4.93
	Wind Zone 3 - 4.20
	Wind Zone 4 - 3.78
Orissa	5.31
Punjab	5.07
Rajasthan	4.46 and 4.69
Tamil Nadu	3.51
Uttarakhand	Wind Zone 1 - 5.15
	Wind Zone 2 - 4.35
	Wind Zone 3 - 3.65
	Wind Zone 4 - 3.20
West Bengal	4.87
Average	**4.448***

Source: Global Wind Energy Council, 2012a.
*Converted to USD using average monthly exchange rate for 2011 of 1 USD = 44.899 INR.

While data for yearly operations and maintenance costs is not widely available, a survey of over 60 projects built in the 2000s revealed an average operations and maintenance cost of 10 USD per MWh of electricity produced (International Renewable Energy Agency, 2012), making the total annual operations and maintenance dependent on project size. The unit cost was used for the models of all three countries and incurred for the lifecycle of the project.

Similar to revenue received from electricity sales, the revenue received from sale of CER credits was forecasted by multiplying the total number of credits by its expected price each year for which credits are received. Since the number of credits is calculated based on comparison with a theoretical business-as-usual baseline and may differ for projects of the same size, it was randomly generated in our models based on an empirically-determined distribution of values from the CDM project database for each country. The expected CER credit prices were simulated in MATLAB using techniques from Tang et al. (2012). We assume that daily returns follow Geometric Brownian motion, with the parameters calibrated from historical price data from 1 September 2009 to 31 August 2010. The CDM allows a single 10-year crediting period or 7-year crediting period which can be renewed. For model simplicity and due to uncertainty surrounding credit renewal, a single value is used for each country's model. In India, the large majority of past projects applied for a 10-year crediting period while projects in both Brazil and China opted for a 7-year crediting period.

Two additional factors were taken into account: 1) probability of project acceptance and 2) delay in receiving credits. The database indicated that, on average, 80.47 percent, 77.5 percent and 97.91 percent of wind energy projects in India, Brazil and China, respectively, were accepted while the others did not receive CDM status. In our simulation, only projects that are approved were built. The database also indicated that there was an average delay of three years until credits are received in India and an average delay of two years in Brazil and China. In the models, this translated into a delay in receiving credit sale revenue which decreases the present value of credit sale revenue. Each investor evaluated each project independently. The initial costs of all built projects were aggregated to produce the total investment in wind energy infrastructure over the simulation time period.

Policy improvements and sensitivity analysis

The first improvement tested is streamlining the approval process for CDM registration and subsequent distribution of CER credits. To capture its effects, the value for delay in receiving CER credits was manipulated. A more efficient process equates to less waiting time to receive credits. Values of zero to five years were used to simulate total investment, holding all other parameters constant.

The second improvement tested is relaxing or eliminating the condition of additionality. In the models, this was equivalent to changing the probability that a project is accepted, with a probability of 1 meaning that "additionality" is excluded from the CDM. Values ranging from 0.6 to 1 in increments of 0.05 were tested holding all other parameters constant. Analysis was not performed for China since 97.91 percent of projects were already approved.

The last improvement tested is to reduce the magnitude of credit price

distortion by stabilizing policy and providing greater clarity on future credit supply. Policy risk is captured in the discount rate of the investors; the more stable the policy, the lower the discount rate. Since there are different discount rates for experienced and inexperienced investors, this is done in terms of change to the discount rate. For example, "+2.5%" indicates an increase of 2.5 percent to both discount rates. Values of -5.0 percent to +5.0 percent in increments of 0.5 percent were tested holding all other parameters constant.

RESULTS

Baseline simulations were performed for *T* equal to 10 years, 15 years, and 20 years for each country. Thirty simulations were executed for each time period and the results for each simulation were averaged to obtain an average total investment for each value of *T*. Since the three countries differ greatly in population and electricity demand, the raw values of total investment are not appropriate for comparisons across countries. Instead, we simulated one more scenario in which we measure total investment in the absence of the CDM by removing the revenue stream from CER credit sales when calculating a project's NPV. Table 14 shows the results for India, Brazil and China and allows us to compare the impact of the CDM in each country. Sensitivity analyses were performed with *T* equal to 10 years. The results are detailed for each country in the following subsections. Again, 30 simulations were executed for each change of the appropriate parameter and then averaged.

Table 14. Average total investment of the "No CDM" and "CDM baseline" scenarios.

	Total investment with no CDM [billions USD]			*Total investment with baseline CDM (as % of no CDM)*		
T	*10*	*15*	*20*	*10*	*15*	*20*
India	1.78	2.89	4.18	2.38 (133%)	3.98 (138%)	5.69 (136%)
Brazil	6.63	9.80	12.8	6.01 (91%)	9.25 (94%)	12.4 (90%)
China	40.0	60.1	79.8	43.3 (108%)	63.8 (105%)	84.0 (105%)

India

The results from Table 14 show total investment of wind energy projects in India increased under the presence of the CDM, indicating that previously unprofitable projects became profitable with additional revenue from CER credit sales and were developed. Figure 18 further demonstrates this point by providing histograms of the NPVs of all wind energy projects considered over 10 years in two sample simulations, one including the CDM and one excluding it. More projects had positive NPVs during the simulation with CDM. However, the majority of projects still had NPVs of less than zero, which indicates that they were rejected by the investor and not built, even with the extra revenue stream.

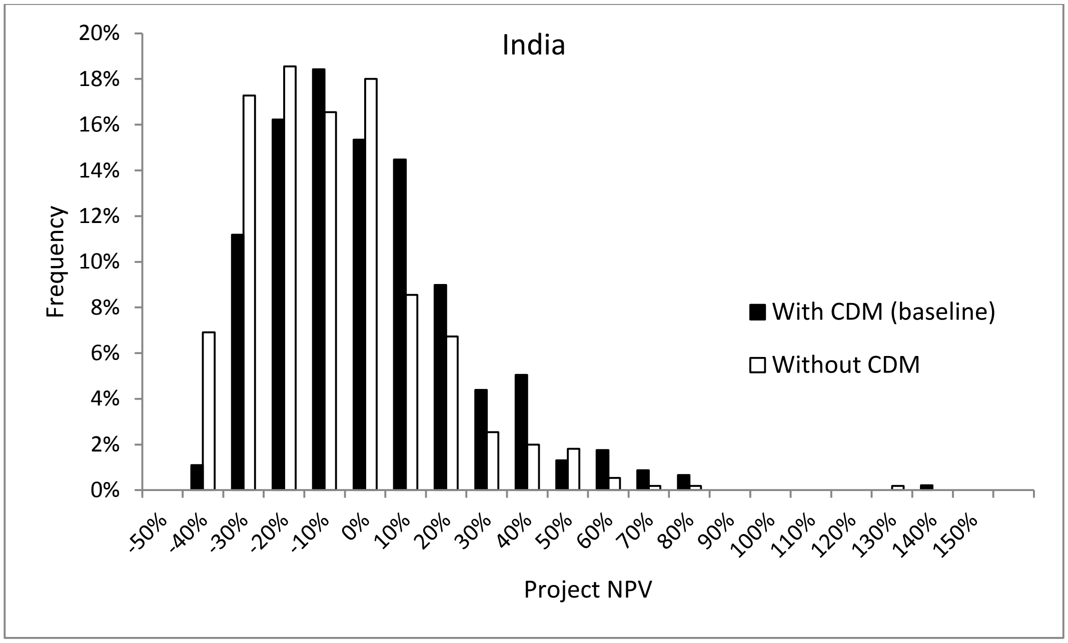

Figure 18. Histogram of NPV of all Indian projects considered in a sample simulation.

Figure 19 shows the impact on total investment when the delay in receiving CER credits was changed as compared to the baseline CDM scenario. The solid black square indicates total investment under the baseline scenario with a wait time of three years. As expected, total investment increased when the delay is shortened, with a linear trend. Under the best case scenario with no delay, total investment grew by over 30 percent.

To test the effect of relaxing or removing the requirement of additionality, we changed the probability of projects being approved and receiving CER credits. If the condition of additionality is completely removed, this is equivalent to the probability equaling 1. Figure 20 shows total investment compared to the baseline scenario. The solid black square represents total investment under the baseline simulation with a probability of 80.57 percent. As expected, total investment increased when the chances of receiving CER credits were increased. Under the best case scenario with guaranteed credits, total investment grew by approximately 35 percent.

Lastly, we used investor discount rate as a proxy for the policy stability, with a decrease in the discount rate representing an increase in stability. Figure 21 shows the total investment compared to the baseline when changing discount rate for both experienced and inexperienced investors. The solid black square represents total investment under the baseline scenario with no changes to either discount rate. Unlike the previous two policy improvements, there appears to be a nearly quadratic relationship between total investment and changes to the discount rate. Additionally, the impact on total investment was greater, reaching 343 percent of baseline total investment if the discount rate decreased by 5 percent.

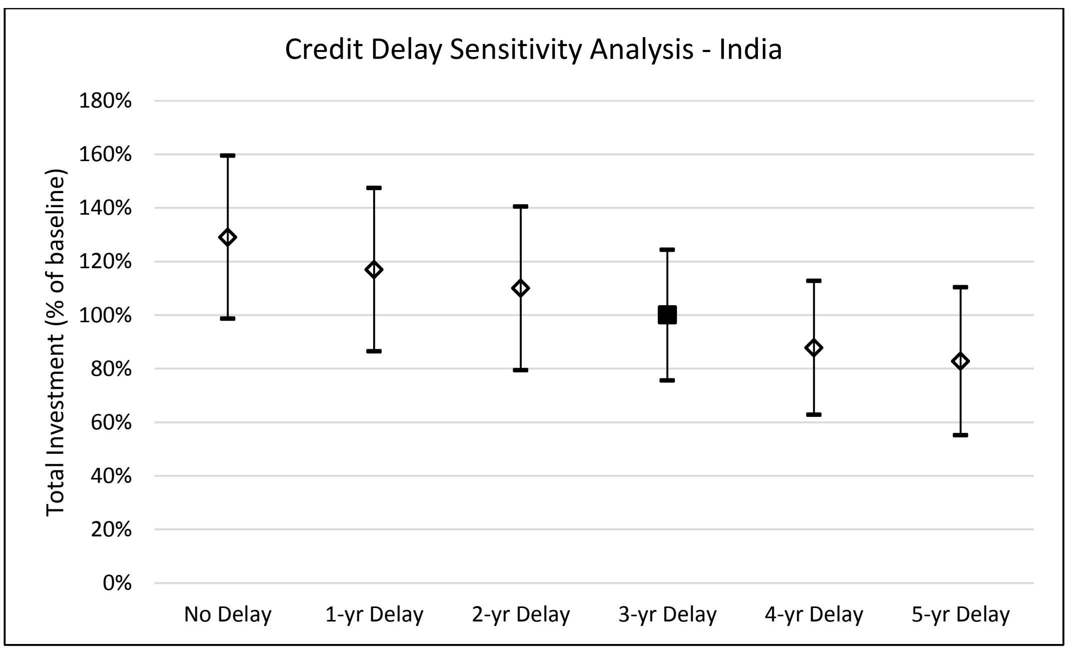

Figure 19. Sensitivity analysis for the delay of issuance of CER credits in India.

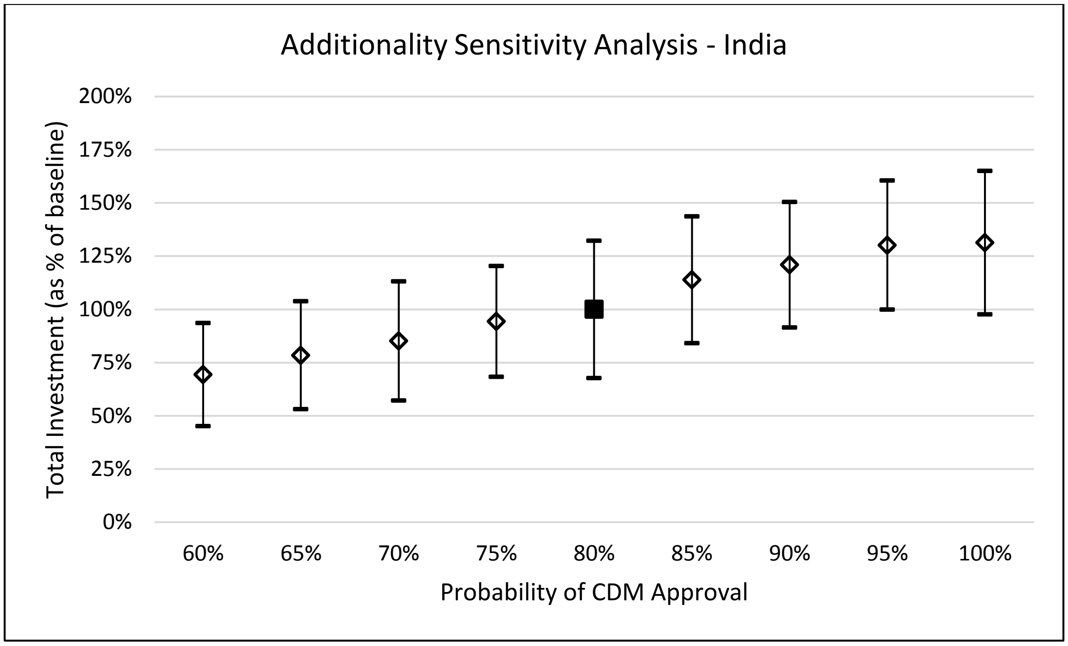

Figure 20. Sensitivity analysis for the probability of CDM program approval in India.

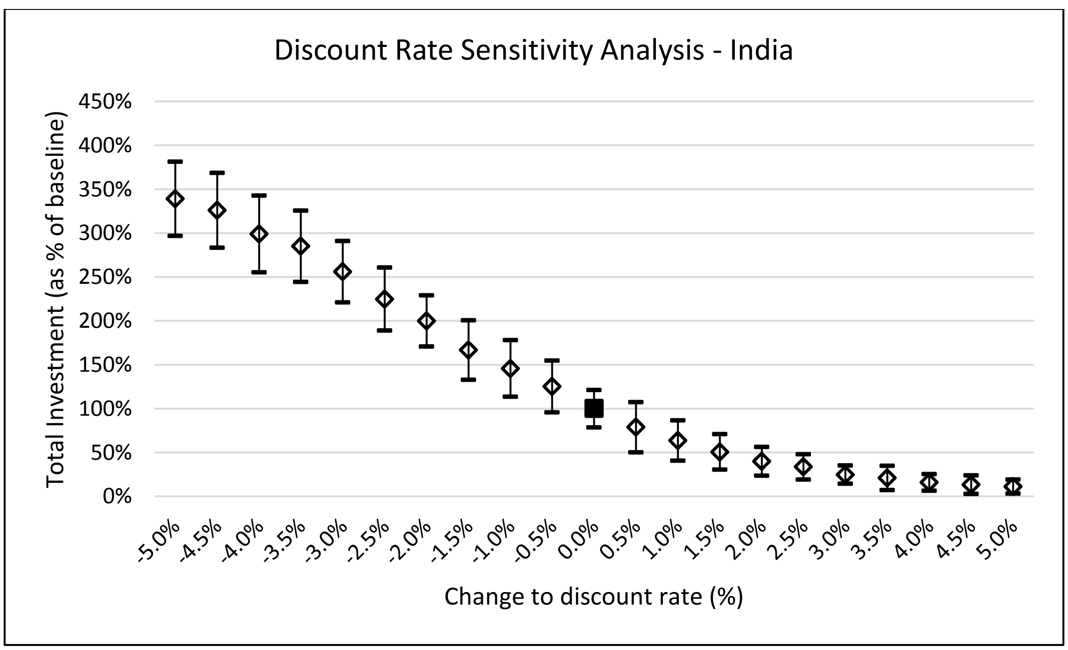

Figure 21. Sensitivity analysis of policy stability (using discount rate as a proxy) in India.

Brazil

For wind energy projects in Brazil, Table 14 shows less investment when the CDM existed as compared to investment without the program. Although counterintuitive, this can happen when profitable projects that are built under the no CDM scenario are not built under the CDM scenario because they did not receive CDM approval. Discussion of this phenomenon can be found in the following section. Figure 22 displays histograms of the NPVs of all wind energy projects considered over 10 years in two sample simulations, one which included the CDM and one which excluded it. Unlike the histogram of project NPVs in India, the aggregate of projects with negative NPVs was approximately the same under both scenarios. In both cases, the majority of projects still had NPVs of less than zero and was not built.

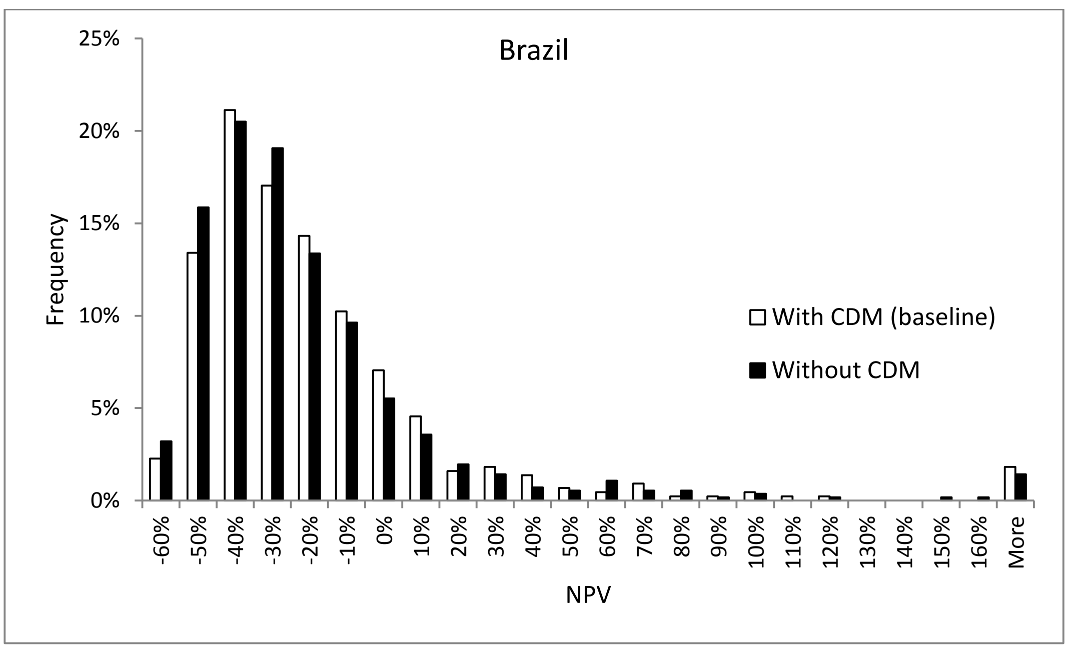

Figure 22. Histogram of NPV of all Brazilian projects considered in a sample simulation.

Figures 23, 24 and 25 show the results of scenario analysis for Brazil of streamlining the approval process, reconsidering additionality, and changes to the discount rate as a result of policy stability, respectively. The solid black squares in each figure represent total investment under the baseline CDM scenario and the top and bottom bars indicate two standard deviations of investment over 30 simulations. Streamlining the approval process and allowing investors to receive CER credits earlier had an almost negligible effect on total investment. Increasing the number of projects receiving CDM status does lead to additional investment, with an increase of 35 percent of all projects are approved. Similar to the results of the India analysis, stabilizing policy and decreasing investor discount rates drastically increased total investment.

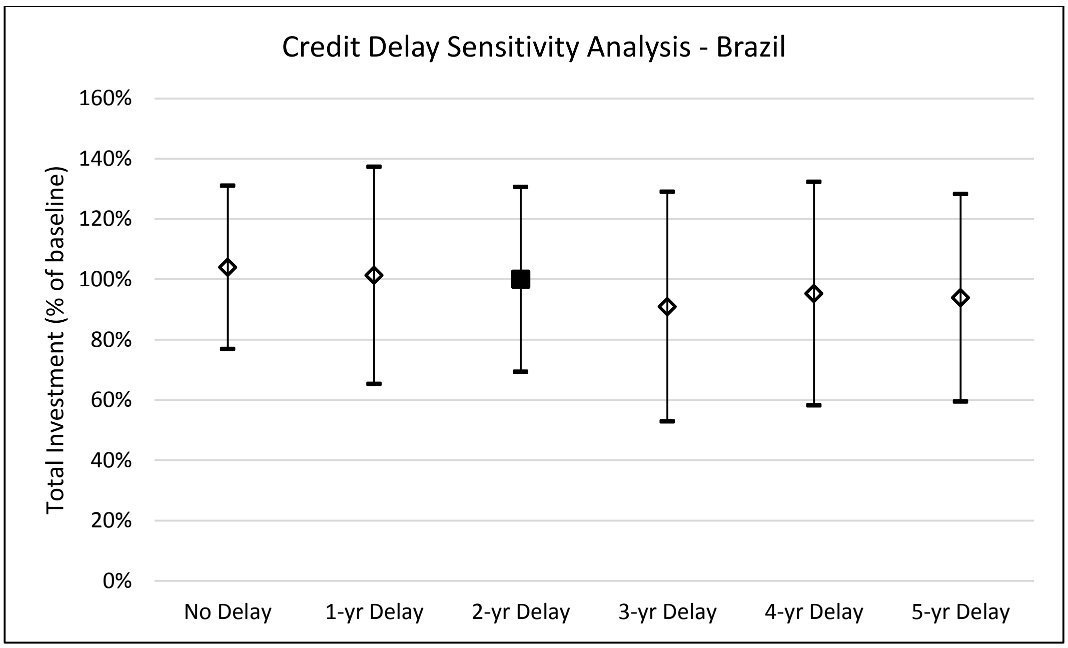

Figure 23. Sensitivity analysis for the delay of issuance of CER credits in Brazil.

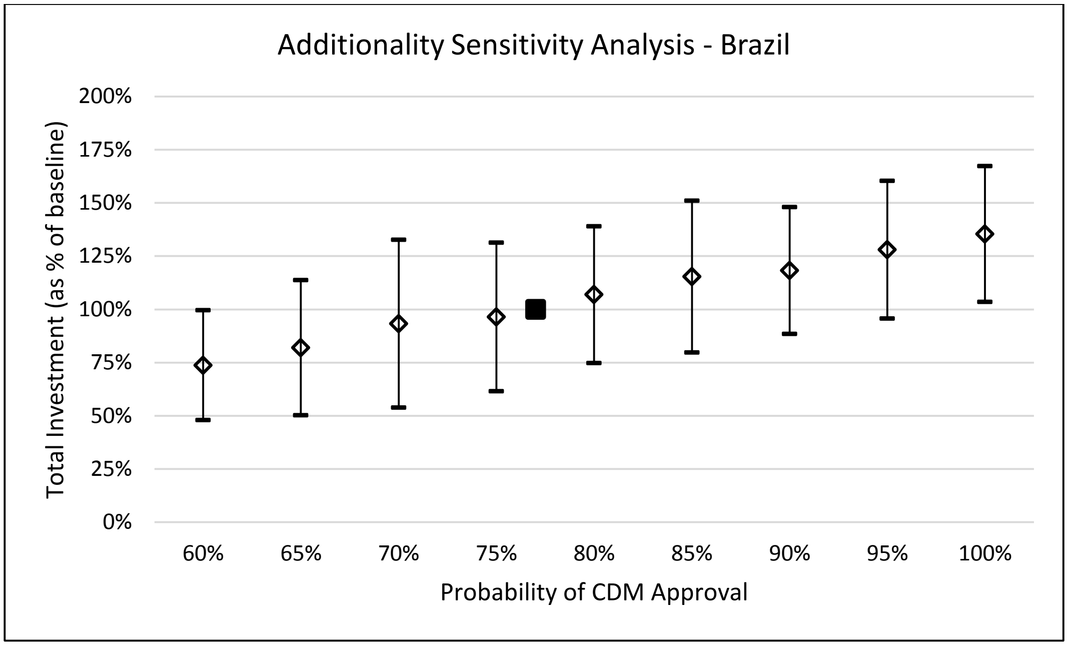

Figure 24. Sensitivity analysis for the probability of CDM program approval in Brazil.

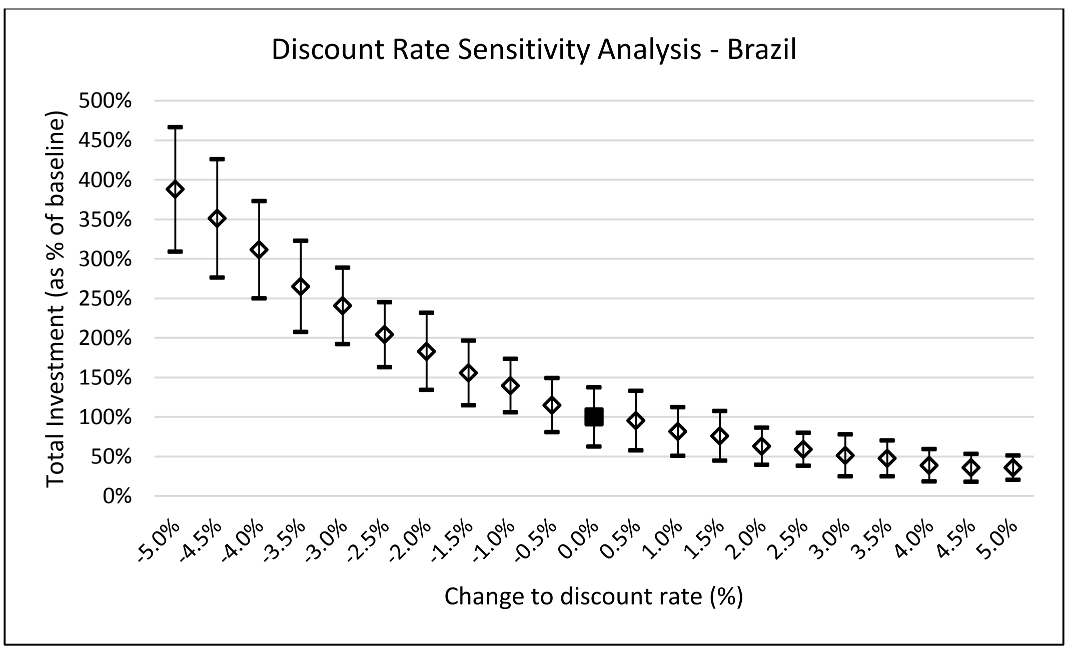

Figure 25. Sensitivity analysis of policy stability (using discount rate as a proxy) in Brazil.

China

The presence of the CDM in China increased total investment in wind energy infrastructure according to the results of Table 14. However, most projects are profitable even without the extra revenue of CER credit sales, as shown in Figure 26. Therefore we can expect that any improvements to the CDM will not drastically increase investment, reflected in Figures 27 and 28. (Because over 97 percent of projects are already receiving CDM project approval, sensitivity analysis was not performed on this parameter). Same as with the results of the previous two countries, the solid black squares represent baseline CDM investment with the top and bottom bars indicating two standard deviations of investment over 30 simulations.

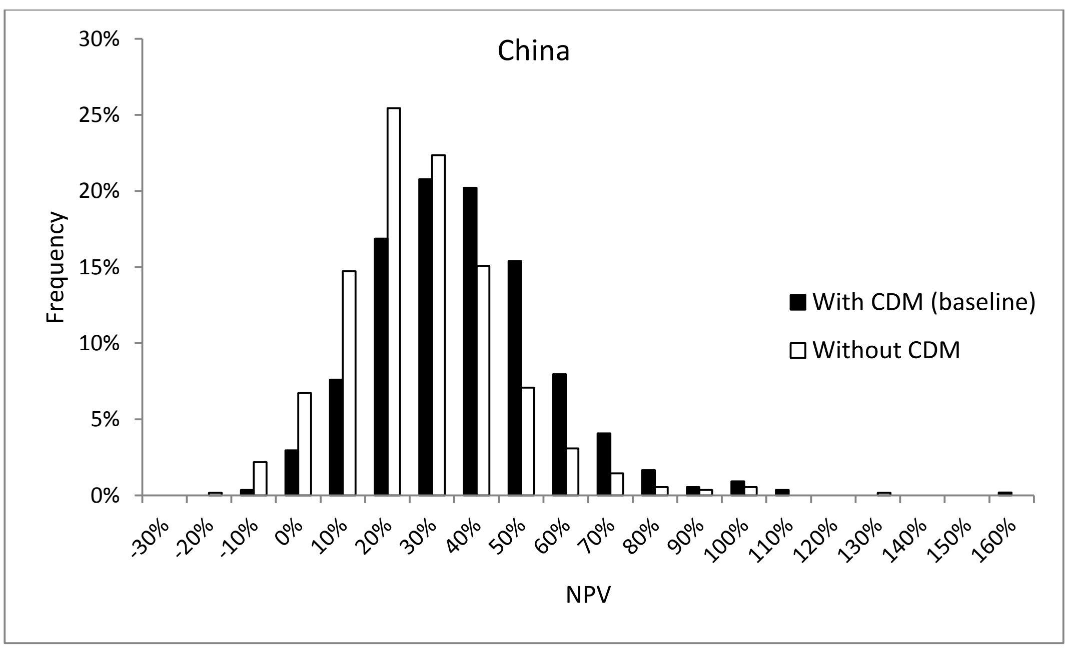

Figure 26. Histogram of NPV of all Chinese projects considered in a sample simulation of T = 10 years.

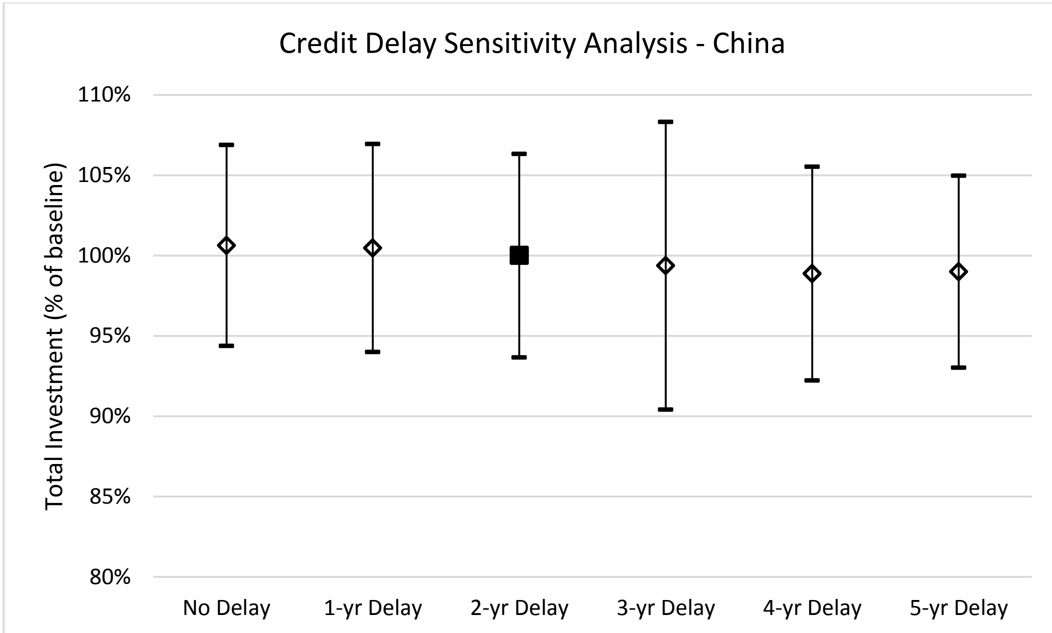

Figure 27. Sensitivity analysis for the delay of issuance of CER credits in China.

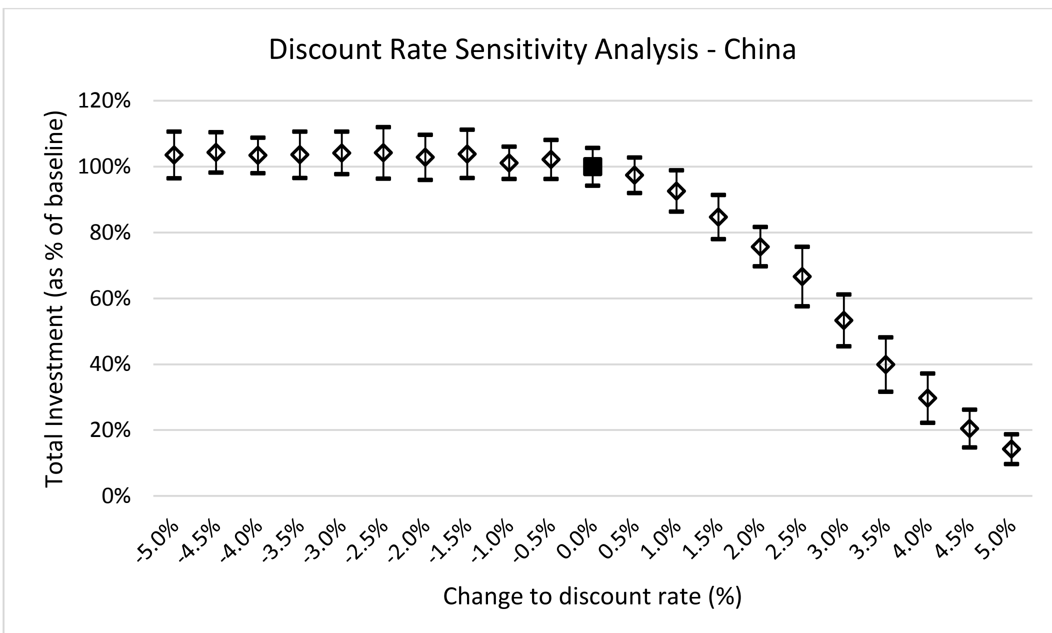

Figure 28. Sensitivity analysis of policy stability (using discount rate as a proxy) in China.

DISCUSSION

Although originally intended as a reference point for scenario analysis of the three policy improvements, the CDM baseline results provide some interesting insights for individual countries and comparison across them. We discuss below two key findings: 1) why most projects considered in China have positive NPVs while the reverse is true for India and Brazil; and 2) why Brazil's level of investment actually decreases under the presence of the CDM. We then discuss the results of the policy improvements to the CDM and its implications for the future of the program as well as other energy policy measures.

Baseline comparison between countries

In the sample simulations of all wind energy projects considered, Figures 18, 22 and 26 show that the NPVs of most projects in India and Brazil are negative and rejected, while most projects in China are profitable and built. Since this is the case for the scenario when the CDM does not exist, we can attribute China's superior performance to the landscape in which projects are developed. A study done by Tang et al. (2013, in press) showed the importance of a comprehensive strategic approach to initiatives used to promote diffusion of renewable energy technologies. We use the strategic structure matrix developed by Tang et al. (2013, in press) as a framework to analyze each country's existing policies.

The matrix breaks down each policy into five different categories in terms of which area it targets. Table 15 summarizes the five categories, and details on development and usage of the matrix can be found in Tang et al. (in press). Table 16 classifies the policies and incentives of each country as discussed in an earlier section of this chapter.

Table 15. The strategic structure matrix.

Lowering a Diffusion Barrier	*Empowering Actors*	*Creating an Enabling Environment*	*Direct or Indirect Influence*	*Supply or Demand*
Technical: decreases uncertainty with technical capabilities *- or -* **Financial**: decreases cost or increases future value *- or -* **Regulatory**: decreases regulatory hurdles to diffusion	**R&D**: increases support of research laboratories and organizations developing new technologies *- or -* **Systems and Infrastructure**: provides support for surrounding infrastructure (physical, market, etc.) *- or -* **Knowledge and learning**: strengthens ties between facilitating organizations	**Institutional Change**: improves institutional landscape for easier diffusion of the technology *- or -* **New/Expanded Market**: creates a new market or expands existing market *- or -* **Advocacy coalition**: creates or promotes pro-diffusion organizations	**Direct**: targeted primary at technology being diffused *- or -* **Indirect**: targeted primary at infrastructure surrounding the technology	**Supply**: ultimately decreases costs or lowers barriers associated with adoption of the technology *- or -* **Demand**: ultimately raises the payoff after adoption of the technology

Source: Tang et al., in press.

Table 16. Classification of country specific policies and incentives.

	Initiative	*Barrier*	*Actor*	*Environment*	*Direct/ indirect*	*Supply/ demand*
India	***Bundle of tax incentives***	Financial	Systems and infrastructure	Market	Direct	Demand
	Feed-in tariffs	Financial	Systems and infrastructure	Market	Direct	Demand
	Loans from IREDA	Financial	Systems and infrastructure	Market	Indirect	Supply
China	***Renewable energy law***	Regulatory	Knowledge and learning	Institutional change	Direct	Supply
	Government-backed banks	Regulatory	Knowledge and learning	Advocacy coalition	Indirect	Supply
	Renewable energy development fund	Technical	Systems and infrastructure	Market	Direct	Supply
	Feed-in tariffs	Financial	Systems and infrastructure	Market	Direct	Demand
Brazil	***Proinfa***	Financial	Systems and infrastructure	Market	Direct	Supply
	Financing from Finame	Financial	Systems and infrastructure	Market	Indirect	Supply
	Wind auctions	Financial	Systems and infrastructure	Market	Direct	Demand

China's policies toward wind power development are more comprehensive in terms of the number of strategies covered. Most notably, its renewable energy law and government involvement in the commercial banking sector is able to overcome regulatory hurdles to diffusion, strengthen ties between facilitating organizations, improve the institutional landscape for wind power deployment, and advance organizations interested in developing more renewable energy infrastructure. These strategic areas are missing from the bundle of policies and incentives offered by India and Brazil, and support previous findings that a comprehensive approach to increasing diffusion is most effective (Tang et al., in press). By doing so, China offered investors stability and reduced risk. It was thought of as a "safe haven" for wind power investment when the effects of the global financial crisis reached the wind industry in other parts of the world (GWEC, 2012b), explaining the low required rates of return found by Donovan and

Nunez (2012) and used as the discount rates in our simulation. The importance of the discount rate to total investment is clear when looking at Figures 21, 25 and 28, which will be discussed in more detail in the following subsection.

Brazil and India's focus on market-forming financial incentives are usually found in the early phases of technology diffusion. While this is understandable for Brazil since it recently entered the market, India has been a part of the wind power industry for over 20 years. India's lack of a comprehensive national policy for wind power combined with the segmented nature of the energy sector emphasizing states is hurting its growth. Researchers agree that a unified vision with national goals is essential for India's continued growth (GWEC, 2012b). As part of a study done by Martins and Pereira (2012), questionnaires were sent to companies, academic and research institutions, and national organizations and associations asking them to rank initiatives to expand renewable energy deployment in Brazil. Two of the highest ranked issues were a) improve government regulations and b) reduce financial risks. For both countries, the sustained regulatory uncertainty means investors will continue to require higher rates of return.

Table 14 shows that total investment in wind energy infrastructure in Brazil actually decreased under the presence of the CDM. This seemingly counterintuitive finding is due to the country's ratio of revenue from electricity sales to CER credit sales. Brazil's wind resources allow increased power production, leading to an average capacity factor of 42.7 percent compared to 23.3 percent for India and 24.5 percent for China (see Table 11). This may be a contributing factor to the low bid prices from investors in recent auctions. However, average capital cost is much higher, leading to the highest frequency of non-profitable projects in our simulation. Unfortunately for Brazil, since CER credits issued through the CDM are based on comparison against a baseline scenario, Brazil's success with hydropower actually hurts its wind industry with respect to participation in the program. The average number of credits it receives for the same size of a wind farm is much less than that received by India or China since Brazil's energy mix is already heavily reliant on emission-free sources. Combined with the higher volume of electricity produced, it means that revenue received from electricity sales matters more than revenue from CER credit sales when calculating NPV. This explains the decrease in investment under the presence of the CDM. The extra credit revenue does little to push unprofitable projects into profitability, while rejection of approximately 33% of projects from the CDM means that they will not be built, even if they are profitable.

China's tight regulatory control over the wind power industry is rare and should not be considered normal for renewable energy development in emerging markets. While the feed-in tariff and CER credit sales generate extra revenue for the investors, some projects are still unprofitable, as presented in our simulation results from India and Brazil. This highlights the need for continued financial support of wind energy infrastructure in emerging economies. Although some projects may be financially feasible without additional government support, to achieve the level of investment necessary to meet future demand, incentives must continue to exist. The different reactions to the CDM from the three countries in our analysis, however, support the view that CDM should play a secondary role and development countries should adopt their own commitments to reduce emissions (Lewis, 2010; Zavodov, 2012).

Policy improvements

Several improvements to the CDM may encourage greater investment in renewable energy infrastructure in emerging markets. Since most of China's wind power projects were already being developed under the CDM baseline simulation, improvements to the program cannot meaningfully increase investment. It should be noted that these improvements may increase the profit margin for individual projects and investors in China. However, the only way to increase total investment is to increase revenue for a proposed project with negative NPV so that it is profitable and subsequently built. Therefore we focus our analysis here on Brazil and India.

Our simulation results shows that streamlining the approval process and shortening the length of time it takes to receive CER credits raises the total level of investment in wind power in India. As a regulatory improvement that strengthens ties between organizations promoting diffusion of wind power, it is unsurprising for India to have such a positive reaction. However, it had a negligible effect on total investment for Brazilian projects. This is likely due to the fact that the revenue from credit sales is less of a factor in calculating NPV as discussed previously. Few unprofitable projects that are already receiving credits will become profitable when changing the present value of credit revenue. Allowing more projects to receive credits, however, does lead to higher investment.

Investments in both India and Brazil increased when the goals of additionality were reconsidered, with total investment rising by 31 percent and 35 percent, respectively. By allowing all renewable energy projects to receive credits regardless of their financial viability in its absence, previously unprofitable projects became profitable, were developed, and increased total investment. This is encouraging to researchers who believe the CDM would be greatly improved without the additionality criteria (Donovan and Nunez, 2012; Lewis, Hultman et al., 2012; Unruh and Carrillo-Hermosilla, 2006).

Most striking, however, is the effect of stabilizing policy and lowering investment risk for developers. A 1 percent decrease in discount rates leads to, on average, 50 percent more simulated projects becoming profitable in India and 56 percent more projects in Brazil, with a doubling of investment realized at a 2 percent decrease in India and a 2.5 percent decrease in Brazil. This has clear implications for policy makers. No matter how attractive they make the financial incentives, having them be stable (for example, longer periods until renewal) will do much more to increase investment. The baseline comparisons between the three countries also echo this fact, as the simulation results for China, the country with the lowest discount rates, show many more projects being realized and higher levels of investment. Additionally, the sensitivity analysis on the Chinese discount rates show investment cut in half when the discount rates increase by 3 percent, which is still lower than the discount rates used for the Brazil simulation. The importance of policy stability and lower risk has been observed historically as well as by many researchers. For example, the appearance and disappearance of tax credits in the US led to a bust-boom development cycle for wind power in the 1990s (Bird et al., 2005; Bolinger et al., 2009; Harper et al., 2007).

CONCLUSION

In an attempt to encourage renewable energy investment, the CDM has provided an incentive for parties from industrialized countries to develop renewable infrastructure in emerging markets. As the future of the CDM is currently being debated, there have been many suggestions to improve the program and address some of its shortcomings, including streamlining its bureaucratic process, relaxing or removing the requirement of additionality, and lowering investor risk by stabilizing policy. We utilized agent-based simulation to quantify total investment in three countries: India, Brazil and China, which are key participants in both the CDM and the global wind power industry. While we intended primarily to evaluate the effects of various regulatory improvements to the CDM, country comparisons of the baseline scenario provided valuable insights. The success of China's wind power development can be attributed in part to a comprehensive approach to renewable energy policy and initiatives, especially the high level of regulatory oversight. However, this should not be considered widespread and the results from India and Brazil reveal the need for continued financial incentives for emerging markets. Our results from the sensitivity analysis of policy improvements show that, compared with the baseline, streamlining the approval process and increasing the odds of project approval has the potential to add significant investment to the wind power sector. However, stabilizing policy is even more effective in increasing the level of investment. This provides key insights to policymakers when designing future policy to encourage renewable development in developing countries. Future research can expand this analysis to other countries that also participate in the CDM and incorporate simulation of investment decisions into larger models of policy evaluation.

Chapter 5

CONTRIBUTIONS

The chapters of this dissertation contribute to the growing body of research from academics who believe the status quo of energy production is unsustainable. The rise of climate change and environmental pollution has put increasing the share of RE in the global energy mix as a top concern for governments worldwide. The findings shared here aid policy makers to design relevant incentives to complement existing regulatory landscapes, quantitatively evaluate the effects of policy changes and create financial mechanisms that address the challenges facing RE investors. The next two sections summarize the individual contributions of the three papers that make up this dissertation and the policy implications they collectively carry.

INDIVIDUAL CONTRIBUTIONS

Chapter 2 – Financing renewable energy infrastructure: formation, pricing and impact of a carbon revenue bond

Chapter 2 reviewed the financing mechanisms that have emerged as a result of energy policy in the US. The proposed carbon revenue bond as a novel financing tool addresses the shortcomings of these financing structures, namely their heavy dependence on tax credits. It builds and extends on previous findings that tax incentives are unstable and ineffective (Bird et al, 2005; Bolinger et al., 2009; Carley, 2009; Carley, 2011) by enhancing credit markets that form around certain regulatory measures and better aligns the timing of the when funds are needed and when incentives are realized. Additionally, it extends application of quantitative methods to model future credit prices as a way to price the bond (Bollerslev, 1986; Brigo et al., 2009, Engle and Ng, 1993; Merton, 1976; Schwartz, 1997). The three illustrative examples presented in Chapter 2 reveal that sale of a carbon revenue bond can meaningfully finance wind energy projects, with median bond values ranging from 15.1 percent to 115 percent of initial costs. The quantitative risk assessment which accompanies the stochastic methodology of bond pricing allows investors to make more informed decisions about the level of risk they are willing to carry. A carbon revenue bond enhances certain regulatory measures and the markets that develop around them. While policies such as the Kyoto Protocol and RPS do not directly address the high initial cost of RE infrastructure, the use of the bond alongside these measures provides developers with pre-development funds. Developers are able to decrease their dependence on tax investors, a subset of investors that have shrunk after the financial downturn (Schwabe et al., 2009). Inclusion of the carbon revenue bond as a primary tool of RE development effectively offsets the higher initial costs associated with RE infrastructure.

Chapter 3 – Strategic structure matrix: a framework for explaining the impact of superstructure organizations on the diffusion of wind energy infrastructure

As described in Chapter 3, the strategic structure matrix extended past research on the relationship between organizations and innovation diffusion. I concentrate analysis on the superstructure organizations of Lynn et al.’s (1996) innovation community framework to determine the role that coordinating organizations including governments have on diffusion of RE infrastructure. Extending beyond research examining how characteristics such as size and heterogeneity affect the influence of organizations (Howells, 2006; Lynn et al., 1996), I focus on how strategies or combination of strategies behind organizational initiatives impact its effectiveness. Previous literature on the relationship between strategy and diffusion on clean-tech as well as innovation in general (Brown and Hendry, 2009; Fernandez de Lucio et al., 2010; Foxon and Pearson, 2008; Jacobson and Bergek, 2004; Jacobsson and Lauber, 2006; Nemet, 2009; Sargsyan et al., 2010) was synthesized to create the five-dimensional categorization of strategies found in the strategic structure matrix. It offers a deeper analysis of the design of initiatives used to encourage RE technologies. The explanatory value of the matrix was texted during a case study of wind power diffusion in five Indian states. The results from case study builds upon past analysis of the Indian RE sector (Bhattacharya and Jana, 2009; Jagadeesh, 2000; Phadke, 2011; Pillai and Banerjee, 2009; Rajsekhar et al., 1999; Rao and Kishore, 2009). It showed that the matrix was successful in explaining why there was more wind power development in certain states by linking the timing of initiatives to empirically derived diffusion curves, using methods from Bass (1969) and Mahajan and Peterson (1985). Additionally, it pinpointed reasons for continued diffusion of wind power in some states and not others. The findings imply that sustained growth in the renewable energy sector requires a comprehensive set of strategies cross all categories and that some initiatives depend on existing support in other strategic areas, consistent with previous literature (Brown and Hendry, 2009; Fernandez de Lucio et al., 2010; Jacobsson and Lauber, 2006; Lynn, 1998). They also support the notation that the effect of incentives are strongly dependent on the existing regulatory environment (Luthi and Prassler, 2011). The strategic structure matrix provides a better understanding of the conditions in which certain policy designs work well and can shape future policy measures.

Chapter 4 – Renewable energy investment in emerging markets: the use of agent-based simulation to evaluate improvements to the Clean Development Mechanism

Chapter 4 detailed the development and use of an agent-based model to simulate investment decisions under different policy scenario. The motivation for this evaluation arose from a lack of studies to quantify the effects of improvements to the CDM. Although the CDM is the primary way in which industrialized countries invest in RE projects in emerging markets (Donovan and Nunez, 2012; Hultman et al., 2012; Lewis, 2010), several of its shortcomings include an opaque and bureaucratic process, questionable effectiveness of additionality, and distorted credit prices arising from policy uncertainties (Dechezlepretre et al., 2008; Donovan and Nunez, 2012; Hultman et al., 2012; Lewis, 2010; Zavodov, 2012). The agent-based simulation improved evaluation of changes to make the CDM a more efficient and effective program by providing quantitative comparison of total investment levels under each scenario. Additionally, it extended the application of agent-based models to evaluate energy policy (de Haan et al., 2009; Eppstein et al.; 2011; Muller and de Haan et al., 2009; Jackson, 2010; Viet et al., 2009). The model was used to simulate investment in wind energy infrastructure in India, Brazil and China, key participants in the CDM and the leading emerging markets for wind power. The pricing method described in Chapter 2 (Tang et al., 2012) was used to calculate future credit revenue and the results of country comparisons further validated the explanatory power of the strategic structure matrix presented in Chapter 3 (Tang et al., 2013, in press). The baseline comparisons between the three countries highlighted the difference in changes to total investment levels under participation in the CDM, supporting findings from previous studies that the effectiveness of the same policy varies based on the existing policy environment and other social objectives (Luthi and Prassler, 2011; Mahadevan and Asafu-Adjaye, 2007; Tang et al, 2013, in press;). Previous researchers advocating for individual country responses to RE development as opposed to continued reliance on the CDM are also bolstered by this finding (Lewis, 2010; Zavodov, 2012). The results of the sensitivity analysis revealed the importance of stabilizing policy and reducing investor risk, reinforcing findings of the Martins and Pereira (2012) survey which cited improving government regulations and reducing risk the two of the top suggestions from academics and industry participants alike to increase RE development.

POLICY IMPLICATIONS

Taken together, the findings from Chapters 2, 3 and 4 carry important implications for the future of energy policy and its associated financing mechanisms. All three chapters, and especially the results of the agent-based simulation in Chapter 4, note the importance of a stable policy which lowers investor risk and increases total levels of development. For example, the federal tax incentives in the US are dependent on budgets and congressional approval. The constant expiration and renewal have created fluctuations in levels of RE development—most noticeably in the Texas wind industry—and have discouraged long-term planning (Bird et al, 2005; Bolinger et al., 2009). The analysis of wind power diffusion in Indian states revealed that Gujarat experienced a period of stagnating investment that coincided with the same period of time when there was an absence of wind energy policies (Roa and Kishore, 2009). A similar situation was observed in Karnataka, where the lack of strong policy signals from the state delayed its entrance into the wind energy industry, despite having high technical potential. The agent-based simulations in India, Brazil and China further stress this point by quantitatively providing evidence that total investment is highly sensitive to investors' discount rates, which in part is determined by the regulatory risks of development. For energy policy to have consistent and substantial impact in aiding RE growth, it must be stable to complement the planning efforts and long lifecycle of RE infrastructure.

The findings in this dissertation also shed an unfavorable light on the long-term value of tax incentives. Use of generous tax benefits requires entities with large tax obligations, which is less advantageous for smaller developers. This explains the heavy depends on tax investors in the US to finance wind energy infrastructure. Unfortunately, the pool of available and interested investors, including investment and commercial banks, decreased after the economic downturn, essentially tying the ability to finance wind power to an outside corporation's tax obligations. In India, accelerated depreciation gave developers the ability to depreciate 100% (later reduced to 80%) of the cost of wind power infrastructure in the first year of operations, also leading to the participation of large corporations. While effective—surveys revealed that tax benefits are the primary reason for investment in wind power (Pillai and Banerjee, 2009; Rajsekhar et al., 1999)—accelerated depreciation awards additional installed capacity but not necessarily more renewable electricity production. Additionally, tax savings act on the demand side (increases rewards after development) and do not help with the high initial costs. The case study in Chapter 3 revealed state governments in India overwhelmingly favored supply side initiatives that lower initial barriers to RE development. Future mechanisms to encourage RE growth should act on the supply side, like the carbon revenue bond presented in Chapter 2.

Lastly, Chapters 3 and 4 highlighted the importance of using different policies in different locations. The effect of the same policy measures on encouraging RE growth is dependent on the current incentive landscape of a country or state, as presented in analysis of the initial diffusion phase of wind energy in India. The simulation results from Chapter 4 reinforced this finding by quantitatively demonstrating the differences in total investment levels under the same policy in three different countries. The findings from Chapter 3 also showed that regulatory measures are more effective on a local level, and a holistic approach to cover all strategic area is valuable to increasing RE diffusion. Therefore new incentives should address the strategic gaps of existing regulation. As the future of the CDM continues to be debated, improvements to the program should be made on a country-by-country basis to address weak strategic areas of existing policy. For example, streamlining the approval process and decreasing bureaucracy increased simulated investments in India but not in Brazil. While the regulations should differ, the markets that trade CER credits should operate on an international basis, as suggested toward the end of Chapter 3.

Together, the research presented in this dissertation contributes to the growing body of literature on how to leverage policy to increase renewable energy development. The carbon revenue bond presents a way to enhance existing policy measures, while the strategic structure matrix and agent-based model are ways to qualitatively and quantitatively create and evaluate new policy initiatives. Continued research in this areas is necessary for the academic community to remain involved in the continued development of RE infrastructure. Doing so allows researchers to sustainably address the issues of rising energy demands and environmental pollution through smart policy and innovative financing.

Chapter 6

SUGGESTED DIRECTIONS FOR FUTURE RESEARCH

While this dissertation addressed some critical issues of how to increase RE development, research is needed for continued growth as part of our evolution into a more sustainable society. In addition to replicating studies in different countries on different technologies, below are three areas in which the work presented here can be extended.

Involvement of institutional investors – This dissertation largely focused on active developers of RE infrastructure assets. Additional research can investigate the ways in which passive investors can participate in RE development. Institutional investors, including pension funds, sovereign funds and university endowments, generally seek long term investment opportunities with a relatively safe risk profile. An interest from these investors to shift away from purely financial assets and into infrastructure has been observed through the emergence of dedicated social impact funds and examples of institutional investments in ports. This represents a growing opportunity for RE to attract an additional pool of investors.

Applications to different energy technologies – The research presented in this dissertation is primarily applied to wind power. Extension of these tools to other energy technologies will continue sustainable growth once wind power approaches its resource potential or achieves self-sustaining growth without the aid of government intervention. Continued use of the strategic structure matrix presented in Chapter 3 can determine if certain strategies or strategic profiles of government incentives are better suited to increase investment in specific technologies. These incentives can also be evaluated for their quantitative impact on investment levels by using the agent-based model presented in Chapter 4, with parameters calibrated to a certain technology in a specific location, for example, the use of solar power in India. Additional efforts can restructure the agent-based model to help governments and planning agencies decide which energy technologies to promote or implement, or how to achieve a particular mix of energy sources. The model can also incorporate the embedded carbon footprint inherent in all renewable technologies, for example, the carbon byproduct of production and disposal of solar cells. This addition can enhance decisions by including the lifecycle environmental impact of renewable energy technologies instead of the impact only during the operating life, and achieve more fully the sustainability goals behind adoption of clean energy.

Broader considerations when evaluating energy policy – The findings of this dissertation could be complemented by taking a broader view of how wind power and other renewable energy technologies interact with one another and the larger energy sector. First, research has shown that early and late adopters of an innovation have different characteristics, and hence different decision making processes for investment in new technologies (Rogers, 2003). We can expect that successful government policies—and on a wider scale, superstructure organization actions—and their strategic structures will differ between the earlier and later stages of diffusion. Future research can expand the role of the strategic structure matrix presented in Chapter 3 into the later stages of diffusion for renewable technologies, especially as the adoption of a certain renewable energy approaches its technical potential. Participating in the later stages of a technology’s diffusion will also change the actions of investors. The agent-based model presented in Chapter 4 assumes that a profitable project will be built without considering the actions of other agents and takes resource availability (e.g. wind and land for project development) for granted, which is more appropriate for the earlier stages of diffusion. As those resources become scarce, investors can be expected to compete for a limited number of projects. Incorporation of agent awareness of the actions or inactions of other agents can enhance the model for use when resource availability becomes problematic. Secondly, many new technologies are developed and patented by individual firms. The intellectual property issues surrounding wide-spread or commercial use of these technologies can increase financial and non-financial costs to adoption and decrease the speed of diffusion. Incorporation of the national or regional attitudes towards intellectual property rights and knowledge sharing into the methodologies presented here can improve analysis of how policy can be leveraged to encourage renewable energy growth.

Interactions of policy enhancements – Lastly, in addition to modeling the interactions of agents with one another, future efforts can evaluate how the three interventions tested in Chapter 4 affect one another. The simulation results assumed that changes to one parameter, such as the percentage of projects receiving approval as a Clean Development Mechanism project, did not impact the other parameters in the model. A more complete analysis can performed by determining the correlation and causal relationships between the factors that affect investment decision using Monte Carlo simulation and other probabilistic methods when evaluating the impact of a policy change on total investment levels.

REFERENCES

AASHTO Center for Excellence in Project Finance, U.S. Department of Transportation. 2011. Transportation Funding and Financing. Available at <http://www.transportation-finance.org/funding_financing/financing/bonding_debt_instruments/municipal_public_bond_issues/revenue_bonds.aspx>. Access date: November 1, 2011.

Barbose, G., Darghouth, N., Wiser, Ryan, Seel, J. 2011. Tracking the Sun IV: An Historical Summary of the Installed Cost of Photovoltaics in the United States from 1998 to 2010. Lawrence Berkeley National Laboratory. LBNL-5047E.

Bass, F.M. 1969. A new product growth for model consumer durables. Management Science 15(5), 215-227.

Bhattacharyya, S.C. 2005. The Electricity Act 2003: Will it transform the Indian power sector? Utilities Policy 13, 260-272.

Bhattacharya, S.C., Jana, C. 2009. Renewable energy in India: historical developments and prospects. Energy 34(8), 981-991.

Bird, L., Bolinger, M, Gagliano, T., Wiser, R, Brown, M., Parsons, B. 2005. Policies and market factors driving wind power development in the United States. Energy Policy 33(11), 1397-1407.

Bolinger, M, Harper, J., Karcher, M. 2009. A Review of Wind Project Financing Structures in the USA. Wind Energy 12(3), 295-309.

Bollerslev, T. 1986. Generalized autoregressive conditional heteroskedasticity. Journal of Econometrics 31, 307-327.

Brigo, D., Dalessandro, A., Neugebauer, M., Triki, F. 2009. A Stochastic Processes Toolkit for Risk Management: Geometric Brownian motion, jumps, GARCH and variance gamma models. Journal of Risk Management in Financial Institutions 2(4), 365-393.

Brown, J., Hendry, C. 2009. Public demonstration projects and field trials: Accelerating commercialisation of sustainable technology in solar photovoltaics. Energy Policy 37(7), 2560-2573.

Burer, M.J., Wustenhagen, R. 2009. Which renewable energy policy is a venture capitalist's best friend? Empirical evidence from survey of international cleantech investors. Energy Policy 37, 4997-5006.

Carley, S. 2009. State renewable energy electricity policies: An empirical evaluation of effectiveness. Energy Policy 37(8), 3071-3081.

Carley, S. 2011. The Era of State Energy Policy Innovation: A Review of Policy Instruments. Review of Policy Research 28(3), 265-294.

Davies, L.L. 2010. Power Forward: The Argument for a National RPS. Connecticut Law Review 42(5), 1139-1403.

de Haan, P., Mueller, M.G., Scholz, R.W. 2009. How much do incentives affect car purchase? Agent-based microsimulation of consumer choice of new cars—Part II: Forecasting effects of feebates based on energy-efficiency. Energy Policy 37, 1083 – 1094.

Dechezlepretre, A., Glachant, M., Meniere, Y. 2008. The Clean Development Mechanism and the international diffusion of technologies: an empirical study. Energy Policy 36, 1273-1283.

Donovan, C., Nunez, L. 2012. Figuring what's fair: the cost of equity capital for renewable energy in emerging markets. Energy Policy 40, 49-58.

Dutra, R.M., Szklo, A.S. 2008. Incentive policies for promoting wind power production in Brazil: scenarios for the Alternative Energy Sources Incentive Program (PROINFA) under the new Brazilian electric power sector regulation. Renewable Energy 33, 65-76.

Energy Information Administration (EIA). 2010a. Annual Energy Outlook 2010 with Projections to 2035. DOE/EIA-0383(2010), April 2010.

Energy Information Administration (EIA). 2010b. Annual Energy Outlook 2011 Early Release Overview. December 2010. Available at <http://www.eia.gov/forecasts/aeo/pdf/0383er(2011).pdf>.

Engle, R. F., Ng, V. K. 1993. Measuring and testing the impact of news on volatility. Journal of Finance 48(5), 1749–1778.

Eppstein, M.J., Grover, D.K., Marshall, J.S., Rizzo, D.M. 2011. An agent-based model to study market penetration of plug-in hybrid electric vehicles. Energy Policy 39, 3789-3802.

Fernandez de Lucio, I., Mas-Verdu, F., Tortosa, E. 2010. Regional innovation policies: the persistence of the linear model in Spain. The Services Industry Journal 30(5), 749-762.

Fordham, J. B. 1942. Revenue Bond Sanctions. Columbia Law Review 42(3), 395-442.

Foxon, T., Pearson, P. 2008. Overcoming barriers to innovation and diffusion of cleaner technologies: some features of a sustainable innovation policy regime. Journal of Cleaner Production 16(1), S148-S161.

Global Wind Energy Council (GWEC). 2012a. India Wind Energy Outlook.

Global Wind Energy Council (GWEC). 2012b. Global Wind Report: Annual Market Update 2012.

Gupta, S. 2012. Financing Renewable Energy, in Toth, F.L. (Ed.), Energy for Development: Resources, Technologies, Environment. Environment and Policy 54, 171-186.

Harish, S.M., Raghavan, S.V. 2011. Redesigning the national solar mission for rural India. Economic and Political Weekly 46(23), 51-58.

Harper, J. P., Karcher, M. D., Bolinger, M. 2007. Wind Project Financing Structures: A Review & Comparative Analysis. Lawrence Berkeley National Laboratory. LBNL-63434.

Howells, J. 2006. Intermediation and the role of intermediaries in innovation. Research Policy 35(5), 715-728.

Hultman, N.E., Pulver, S., Guimaraes, L., Deshmukh, Kane, J. 2012. Carbon market risks and rewards: firm perceptions of CDM investment decisions in Brazil and India. Energy Policy 40, 90-102.

International Energy Agency (IEA). 2008. Energy Technology Perspectives 2008 - Scenarios and Strategies to 2050. IEA Publications, Paris.

International Renewable Energy Agency. 2012. Renewable Energy Technologies: Cost Analysis Series. IRENA Secretariat, Abu Dhabi.

Jackson, J. 2010. Improving energy efficiency and smart grid program analysis with agent-based end-use forecasting models. Energy Policy 38, 3771-3780.

Jacobsson, S., Bergek, A. 2004. Transforming the Energy Sector: The evolution of technological systems in renewable energy technology. Industrial and Corporate Change 13(5), 815-849.

Jacobsson, S., Lauber, V. 2006. The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology. Energy Policy 34(3), 256-276.

Jagadeesh, A. 2000. Wind energy development in Tamil Nadu and Andhra Pradesh, India: intuitional dynamics and barriers – a case study. Energy Policy 28(3), 157-168.

Jiang, L., Chi, Y., Qin, H., Pei, Z., Li, Q., Liu, M., Bai, J., Wang, W., Feng, S., Kong, W., Wang, Q. 2011. Wind Energy in China. IEEE Power and Energy Magazine, November/December 2011, 36-46.

Kahn, E. 1996. The production tax credit for wind turbine powerplants is an ineffective incentive. Energy Policy 24(5), 427-435.

Langniss, O., Wiser, R. 2003. The renewables portfolio standard in Texas: an early assessment. Energy Policy 31(6), 527–536.

Leahy, J. 2013. "Brazil: wind gathers force in mix of renewable sources." Financial Times: 15 May 2013.

Lewis, J.I. 2010. The evolving role of carbon finance in promoting renewable energy development in China. Energy Policy 38, 2875-2886.

Liming, H. 2009. Financing rural renewable energy: a comparison between China and India. Renewable and Sustainable Reviews 13, 1096-1103.

Luthi, S., Prassler, T. 2011. Analyzing policy support instruments and regulatory risk factors for wind energy deployment—a developer's perspective. Energy Policy 39, 4876-4892.

Lynn, L.H. 1998. The commercialization of the transistor radio in Japan: the functioning of an innovation community. IEEE Transactions on Engineering Management 45(3), 220-229.

Lynn, L.H., Reddy, N.M., Aram, J.D. 1996. Linking technology and institutions: the innovation community framework. Research Policy 25(1), 91-106.

Mahadevan, R., Asafu-Adjaye, J. 2007. Energy consumption, economic growth and prices: a reasssessment using panel VECM for developed and developing countires. Energy Policy 35(4), 2481-2490.

Mahajan, V., Peterson, R.A. 1985. Models for Innovation Diffusion. Sage Publications, Inc., Newbury Park.

Martins, F.R., Pereira, E.B. 2011. Enhancing information for solar and wind energy technology deployment in Brazil. Energy Policy 39, 4378-4390.

Masini, A., Menichetti, E. 2012. The impact of behavioural factors in the renewable energy investment decision making process: conceptual framework and empirical findings. Energy Policy 40, 28-38.

Menz, F. C., Vachon, S. 2006. The effectiveness of different policy regimes for promoting wind power: Experiences from the states. Energy Policy 34(14), 1786-1796.

Merton, R. C. 1976. Option pricing when underlying stock returns are discontinuous. Journal of Financial Economics 3(1-2), 125–144.

Morthorst, P. E. 2004. Wind Energy - The Facts: Volume 2 Cost and Prices. European Wind Energy Association (EWEA).

Mueller, M.G., de Haan, P. 2009. How much do incentives affect car purchase? Agent-based microsimulation of consumer choice of new cars—Part I: Model structure, simulation of bounded rationality, and model validation. Energy Policy 37, 1072-1082.

Nemet, G.F. 2009. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. Research Policy 38(5), 700-709.

Nogee, A., Deyette, J., Clemmer, S. 2007. The Projected Impacts of a National Renewable Portfolio Standard. The Electricity Journal 20(4), 33-47.

North Carolina Solar Center. 2010. Database of State Incentives for Renewable Energy (DSIRE). Available at <http://www.dsireusa.org>. Access date: November 15, 2010.

Palmer, K., Paul, A., Woerman, M., Steinberg, D. C. 2011. Federal policies for renewable electricity: Impacts and interactions. Energy Policy 39(7), 3975-3991.

Phadke, A., Bharvirkar, R., Khangura, J. 2011. Reassessing Wind Potential Estimates for India: Economic and Policy Implications. Lawrence Berkley National Laboratory LBNL-5077E.

Pillai, I.R., Banerjee, R. 2009. Renewable energy in India: status and potential. Energy 34(8), 970-980.

Poole, R. W., Orski, C. K. 2003. HOT Networks: A New Plan for Congestion Relief and Better Transit. Reason Public Policy Institute. Policy Study 305.

Rabe, B. 2011. Contested Federalism and American Climate Policy. Publius: The Journal of Federalism 41(3), 494-521.

Raghavan, S.V., Bharadwaj, A., Thatte, A.A., Harish, S., Iychettira, K.K., Perumal, R., Nayak, G. 2010. Harnessing Solar Energy: Options for India. Center for Study of Science, Technology and Policy, Bangalore.

Rajsekhar, B., Van Hulle, F., Jansen, J.C. 1999. Indian wind energy programme: performance and future directions. Energy Policy 27(11), 669-678.

Rao, K.U., Kishore, V.V.N. 2009. Wind power technology diffusion analysis in selected states of India. Renewable Energy 34(4), 983-988.

Reddy, N.M., Rao, H. 1990. The industrial market as an interfirm organization. Journal of Management Studies 27(1), 43-59.

REN21. 2012. Renewables 2012 Global Status Report. Renewable Energy Policy Network for the 21st Century. REN21 Secretariat, Paris.

Rogers, E. 2003. The Diffusion of Innovations, fifth ed. Free Press, New York.

Rohracher, H. 2002. A sociotechnical mapping of domestic biomass heating systems in Austria. Bulletin of Science, Technology and Society 22(6), 474-483.

Sadorsky, P. 2012. Modeling renewable energy company risk. Energy Policy 40, 49-48.

Sargsyan, G., Bhatia, M., Banerjee, S.G., Raghunathan, K., Soni, R. 2010. Unleashing the Potential of Renewable Energy in India. The World Bank Publications, Washington DC.

Scheer, H. 2006. Energy Autonomy: the Economic, Social and Technical Case for Renewable Energy. Routledge, London.

Schwabe, P., Cory, K., Newcomb, J. 2009. Renewable Energy Project Financing: Impacts of the Financial Crisis and Federal Legislation. National Renewable Energy Laboratory. NREL/TP-6A2-44930.

Schwartz, E. S. 1997. The stochastic behavior of commodity prices: Implications for valuation and hedging. Journal of Finance 52(3), 923–973.

Tang, A., Chiara, N., Taylor, J.E. 2012. Financing renewable energy infrastructure: formation, pricing and impact of a carbon revenue bond. Energy Policy 45, 691-703.

Tang, A., Taylor, J.E., Mahalingam, A. 2013. Strategic Structure Matrix: A framework for explaining the impact of superstructure organizations on the diffusion of wind energy infrastructure. Energy Policy *(in press)*.

Unruh, G.C., Carrillo-Hermosilla, J. 2006. Globalizing carbon lock-in. Energy Policy 34(10): 1185-1197.

Veit, D.J., Weidlich, A., Kraft, J.A. 2009. An agent-based analysis of the German electricity market with transmission capacity constraints. Energy Policy 37, 4132-4144.

Wiser, R. H. 1997. Renewable energy finance and project ownership. Energy Policy 25(1), 15-27.

Wiser, R., Namovicz, C., Gielecki, M., Smith, R. 2007. The Experience with Renewable Portfolio Standards in the United States. The Electricity Journal 20(4), 8-20.

Zavodov, K. 2012. Renewable energy investment and the clean development mechanism. Energy Policy 40, 81-89.