A dynamic perspective on environmental innovation and national competitiveness - an assessment of policy and empirical evidence from the solar energy sector

Doctoral thesis submitted to the
Department of Political and Social Sciences
Freie Universität Berlin

In fulfillment of the degree of Dr. rer. pol. in Political Sciences

Presented by Rainer Quitzow

Supervisor and first examiner: Dr. Klaus Jacob
Second examiner: Professor Dr. Miranda Schreurs

Defended on July 2, 2015

Submitted May 2015

Dedicated to

Luana

Acknowledgements

I would like to hereby thank the various formal and informal supervisors and mentors, colleagues, friends and family members, who have accompanied me in the journey of this doctoral thesis. It has been an enriching and enjoyable process which I am glad to have shared with all of you.

First and foremost, I would like to thank Klaus Jacob for providing me with the unique opportunity to pursue this thesis project within the Policy Assessment Group at the Environmental Policy Research Centre (FFU). The group's work at the nexus of policy and research has not only provided me with a stimulating environment for developing and refining the ideas captured in this doctoral thesis. It has also offered the highly rewarding opportunity to apply my evolving insights to help solve ongoing policy challenges and thereby ground them in the practice of policy making. Moreover, I am very grateful for the thoughtful feedback I received from Klaus on various drafts of this thesis as well as our continuous discussions on both the theoretical and practical relevance of my work.

I would also like to thank Miranda Schreurs, Martin Jänicke and all the great colleagues at FFU for the countless discussions and helpful advice provided along the way. In particular, I would like to thank Dörte Ohlhorst, Sibyl Steuwer, Stefan Werland, Robert Brandt, Helge Jörgens, Holger Bär and Sabine Weiland who provided feedback on different parts of this thesis. Moreover, I would like to thank Kirsten Jörgensen for providing me with the wonderful opportunity to visit India as a part of the DAAD-financed exchange program between TERI University and FFU, a crucial contribution to the field work performed for this thesis.

Another important source of inspiration and feedback were the various partners within the project *Lead Market Strategies: First Mover, Early Follower and Late Follower*, the principal funding source for my doctoral project (financed by the Federal Ministry of Education and Research under its framework program *Research for Sustainable Development*, FONA). The work within the project team offered a highly constructive and supportive work environment, yielding among other things the joint publication submitted as part of this doctoral thesis. In this vein, a special thank you goes out to my co-authors Rainer Walz, Jonathan Köhler (both Fraunhofer ISI) and Klaus Rennings (ZEW).

I would also like to acknowledge the important support I received from Bernhard Truffer and Christian Binz (both at EAWAG at the time) during the writing of the paper on the development of the solar energy sector in China and Germany. I am very grateful for their valuable comments and constructive feedback on multiple drafts of the paper. In addition, I am grateful for the review of the empirical evidence in the paper by Lars Waldmann (Agora Energiewende) and Lv Fang (IEA PVPS, China). The paper on India's National Solar Mission has benefitted from comments received at various conferences and workshops from a number of scholars, including Anna Bergek (Linköping University), Adrian Ely (SPRU, University of Sussex), Daisuke Hayashi (Ritsumeikan University) and Margaret Taylor (Lawrence Berkeley National Laboratory).

Another important thank you goes out to the colleagues in China and India who supported me during the field work I conducted there. I would like to thank Wang Yi and Chen Shaofeng for hosting me at the Institute of Policy and Management of the Chinese Academy of Sciences as well as Xingjun Ru, Su Liyang and Lifeng Yang (all PhD candidates at the Institute of Policy and Management at the time) and Yudong Zhou (Institute of Electrical Engineering, Chinese Academy of Sciences) for supporting me in various ways during my stay. In Delhi, I would like to thank Rajiv Seth and Joachim Schmerbeck

for facilitating my stay at TERI University as well as the various colleagues at TERI, including Leena Srivastava, Arabinda Mishra, Navarun Varma and Ankita Narain, for their kind support during my stays in India.

Finally, I would like to thank my parents, Grace and Wilhelm, and my wife, Luana. They have supported me throughout the process of writing this thesis. The boundless energy and encouragement of Luana - who incidentally gave birth to my two children Jan Marco and Luciana during the period of my doctoral project - have been a particular inspiration and have made the process a particularly joyful one. It is for this reason that I have dedicated the thesis to her.

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List of abbreviations

ATM	Automated teller machine
BMBF	German Federal Ministry of Education and Research
CDB	China Development Bank
CEO	Chief executive officer
CERC	Central Electricity Regulatory Commission
CSP	Concentrated solar power
DCR	Domestic content requirement
EU	European Union
FB	Feedback
FFU	Environmental Policy Research Centre at Freie Universität Berlin
GIZ	German Agency for International Cooperation
IEA	International Energy Agency
IPO	Initial public offering
IREDA	Indian Renewable Energy Development Agency
IS	Innovation systems
JNNSM	Jawaharlal Nehru National Solar Mission
KfW	Kreditanstalt für Wiederaufbau (Germany's development bank)
LMI	Lead market initiative
MBR	Membrane bioreactor technology
MLP	Multi-level perspective
MNRE	Indian Ministry of New and Renewable Energy
NCEF	National Clean Energy Fund
NIS	National Innovation System
NTPC	National Thermal Power Corporation
NVVN	A subsidiary of NTPC
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturer
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme of the IEA
R&D	Research & Development
RGGVY	Rajiv Ghandi rural electrification scheme
ROW	Rest of the World
RVEP	Remote Village Electrification Programme
SECI	Solar Energy Corporation of India
SI	Systems of innovation
SNM	Strategic niche management
SSI	Sectoral systems of innovation
TIS	Technological innovation system
TL	Transnational linkage
TM	Transition management
UNSW	University of New South Wales in Sydney
US	United States of America
VC	Venture capital

Summary

It is widely accepted that sustainable development is dependent on innovation in environmental technologies and their global diffusion. Simultaneously, innovation in environmental technologies is increasingly perceived as a pathway to sustaining national competitiveness and enabling future economic development. Correspondingly, global competition in the field of environmental technologies has increased markedly. Not only industrialized countries - the traditional leaders in this field - but China and other emerging economies are positioning themselves to capture leadership positions in the related industries (Gallagher 2014).

Increased global competition is placing pressure on policy makers to help domestic firms compete in this growing sector of the economy. As pointed out in the European Commission's 2020 growth strategy, Europe's first mover advantages in the field of green solutions are being challenged by important competitors, most notably the US and China (European Commission 2010, p. 14). The questions that this raises are particularly controversial, as markets for environmental technologies are typically policy-driven. Market support policies play a crucial role in enabling the development and diffusion of these technologies (Jänicke & Lindemann 2010).

In this context, market support for environmental technologies is increasingly viewed as a new generation of industrial policy. Rather than representing a mere subfield within the realm of environmental policy, it is considered a strategic investment in building a competitive advantage in an emerging industrial sector. At the same time, the growing role of emerging economies and the related competitive pressures are raising new questions regarding the effectiveness of such a green industrial policy approach. In the field of solar photovoltaics, for instance, critics have argued that German market support has mainly benefited suppliers abroad, most notably in China (EFI 2013; BMBF 2011).

Against this background, this thesis seeks to answer the following inter-related questions:

1. *How are developments in important emerging economies influencing the global dynamics of innovation and economic competition in policy-driven markets for environmental technologies?*
2. *What are the implications of these global dynamics for the design and assessment of policies aimed at promoting innovation in environmental technologies, while sustaining national competitiveness?*

The thesis consists of four papers, two of which aim to answer the first research question (Papers #1 and #2) and two of which focus on answering the second research question (Papers #3 and #4). Each pair of papers includes both a primarily conceptual (Papers #1 and #3) and a primarily empirical contribution (Papers #2 and#4). Both empirical papers draw on case studies of the solar energy sector, more specifically the field of solar photovoltaics (PV). As an archetypical example of a policy-driven market, the solar photovoltaics sector is a particularly suitable case for exploring the questions outlined above. Conceptually, all four papers build on evolutionary and system-based approaches to studying environmental innovation and technological change. In particular, they draw on literature in this field, which discusses the link between environmental innovation and national competitiveness and the role of policy in this context.

The contribution of each paper is briefly outlined in the following:

Paper #1: The concept of "lead markets" revisited: Contribution to environmental innovation theory

Paper #1 focuses on the lead market concept and discusses its key contributions to the literature on environmental innovation and as well as policy debates on the relationship between environmental innovation and economic competitiveness. It finds that it offers a unique approach for capturing how the role of cross-country competitive dynamics influences the global diffusion of environmental innovations. Hence, the concept has also offered an important entry point for policy debates on the promotion of environmental innovation and national competitiveness. Moreover, the literature on lead markets has offered important empirical evidence of the global diffusion of policy-driven markets for environmental technologies. In doing so, it has provided an empirical basis for the claim that ambitious and well-designed environmental policies may provide early mover advantages for firms in countries that anticipate global regulatory trends.

At the same time, the lead market concept suffers from a number of important weaknesses. Among a number of gaps that are identified, two are particularly salient for addressing the first of the two research questions formulated above. Firstly, the original lead market literature has focused exclusively on competition between OECD countries. It does not yet reflect the increasing role of emerging economies, in particular China, within the global economy in general and in the field of environmental technologies in particular. Secondly, the lead market concept builds on the strong assumption that the global diffusion of demand typically precedes the globalization of supply in emerging industries. The dynamics of supply-side competition *during* the process of lead market development are not considered. To close these important gaps in the literature, the paper outlines a number of questions for further research. Among other things, it calls for research on the dynamic interaction between lead and lag markets within a global system of innovation. It is this question that is taken up in the following paper (Paper #2).

Paper #2: Dynamics of a Policy-Driven Market: The Co-evolution of Technological Innovation Systems for Solar Photovoltaics in Germany and China

Based on the concept of technological innovation systems (TIS), paper #2 develops an analytical framework for analyzing the role of geographical differences and cross-country inter-dependencies in the dynamic development of emerging technology fields. The central pillar of this framework is the set of seven system functions developed by Hekkert et al. (2007) for the analysis of TIS functional dynamics. Adding to this, the paper proposes the concept of asymmetrical yet co-evolving country-level TIS. The concept of co-evolution is defined as a development process characterized by reciprocal influences between two or more sub-systems. These reciprocal influences in turn are enabled by what is referred to as direct transnational linkages as well as more indirect channels, which manifest themselves in the form of cross-country spillovers and feedbacks.

This analytical framework is applied for the dynamic analysis of the co-evolutionary process of TIS development in the field of crystalline-based solar PV technologies, focusing on developments in Germany and China between 1999/2000 and 2010/2011. The central empirical finding of the paper is that developments in Germany and China were not only inter-dependent but also highly complementary in enabling the development of the sector. While developments in German were crucial drivers of the rapid expansion of demand, the Chinese system of innovation and production represented a key to global supply-side expansion and the resulting cost reductions. It was this

combination of inter-related developments, which enabled the dynamic development of the sector during the time period under consideration.

These empirical findings validate the proposed concept of co-evolving country-level TIS and provide the basis for revising the previous lead-lag market assumption. Although the chosen case study can only describe one alternative development pathway to the previous lead-lag market model, it offers a first entry-point for exploring different types of global development trajectories.

Paper #3: Towards an integrated approach to promoting environmental innovation and national competitiveness

Paper #3 explores the more focused question of how governments can promote environmental technologies while sustaining national competitiveness. The paper provides a review of the existing literature on innovation-oriented environmental policy, exploring neoclassical approaches and approaches rooted in evolutionary theories of economic development and technological change. These approaches are then contrasted with current debates in the literature on economic development and growth. Key finding of the paper is that recent advances in the latter literature are making its policy implications increasingly compatible with those from evolutionary approaches to innovation-oriented environmental policy. Both acknowledge that innovation and technological change are highly country-specific processes, which require adaptive policy mixes tailored to the particular innovation system. Moreover, designing and implementing such a policy mix – whether to promote economic competitiveness or more environmentally friendly technologies – requires the same basic set of governance mechanisms. These findings suggest increasing scope for integrating policies for the promotion of environmental innovation and economic competitiveness.

To develop such an approach in practice requires an explicit consideration of the dynamics of international competition and technological change. Drawing on examples from the German wind and solar sectors, the paper argues that pioneering environmental policies do offer opportunities for building longer term competitive advantage. However, the particular outcome depends on additional factors, like the domestic endowment structure and the ability of domestic firms to compete in particular segments of the supply chain. An integrated approach to promoting environmental innovation and national competitiveness, the paper concludes, should combine policies to enable environmental innovation with targeted supply-side measures to support the most promising segments of the emerging supply chain. Finally, competition in markets for environmentally-friendly products and technologies is not only a matter of economic competition but depends also on the diffusion of the related standards and regulatory solutions. Hence, a further element of an integrated approach to environmental innovation and national competitiveness is captured in the concept of an "environmental foreign policy" (Jacob & Bär 2014). An active promotion of the transfer of domestic regulatory frameworks can serve as a vehicle for encouraging related technology exports.

Paper #4: Assessing policy strategies for the promotion of environmental technologies: A review of India's National Solar Mission

Building on the perspective developed in paper #3, paper #4 then develops a framework for assessing policies for the promotion of environmental technologies. The paper begins with a critical review of the literature on policy mixes and related approaches for their assessment. It finds that the existing literature has defined a number of generic concepts for assessing the suitability of policy

mixes, which are unrelated to any particular policy field. Rayner and Howlett (2009) state that so-called “optimal integrated policies” require a policy design “in which multiple policy goals can be coherently pursued at the same time, and second, policy instrument mixes are consistent in the sense of being mutually supportive in the pursuit of policy goals” (p.100). The paper challenges the concept of an optimal policy mix and its emphasis on coherence and consistency as central assessment criteria. Instead it highlights the normative dimension of policy making and the need to balance inherent policy trade-offs within a given policy mix.

On this basis, the concept of a *policy strategy* is proposed as an alternative to the existing policy mix concept. Drawing on existing literature as well advisory work conducted for the German Ministry of the Environment by the Policy Assessment Group at the Environmental Policy Research Centre (Jacob et al. 2012), a policy strategy is defined as the combination of the following three elements:

- *Strategy content*, composed of policy objectives and the measures designed to achieve them;
- *Strategy process*, encompassing the process of policy development, implementation and adaptation;
- *Strategic capacity*, including the capacities need for policy development, implementation and learning as well as the engagement of stakeholders.

This generic strategy concept represents the basis for the subsequent development of a framework for the assessment of strategies for promoting environmental technologies. Building on a co-evolutionary perspective on environmental innovation and technological change, detailed assessment criteria for each of the elements are derived from the literature.

Finally, the assessment framework is applied in an exemplary fashion to India’s Jawaharlal Nehru National Solar Mission (JNNSM). A key result of the assessment is that unresolved trade-offs between demand- and supply-side objectives are hampering implementation of the strategy. Furthermore, strong market support has come at the expense of measures to support other important system functions, such as the mobilization of resources and knowledge development and diffusion. To tackle both issues, the paper highlights the importance of *process* and *capacity* considerations. In particular, the paper identifies the need for a more active engagement of stakeholders in the policy process and the development of capacities for implementing effective supply-side measures.

The paper concludes with a discussion of possible future applications as well as remaining weaknesses of the assessment framework. A key weakness of the framework - as well as the underlying literature - is the lack of more nuanced criteria for considering the political dimension of policy trade-offs. The development of criteria and analytical tools for incorporating political factors in policy strategies for promoting environmental technologies represents an important avenue for future research. One important step in this direction might be the systematic cross-country comparison of policy strategies and how these are embedded and shaped by country-specific governance mechanisms and political conditions. The proposed strategy concept offers an analytical framework for conducting such comparative analyses. In a further step, such an analysis might address the interplay between different country-level strategies, an issue of increasing importance within the context of emerging technology fields.

Zusammenfassung

Es ist allgemein anerkannt, dass eine nachhaltige Entwicklung unter anderem von der Entwicklung und globalen Ausbreitung von Umwelttechnologien[1] abhängt. Gleichzeitig, wird Innovation im Bereich der Umwelttechnologie als ein Ansatz zur Stärkung nationaler Wettbewerbsfähigkeit und zur Förderung zukünftiger wirtschaftlicher Entwicklung gesehen. Dementsprechend, hat der globale Wettbewerb in diesen Technologiefeldern stark zugenommen. Nicht nur Industrieländer, die in diesem Bereich traditionell die Führungsrolle übernommen haben, sondern auch China und andere Schwellenländer positionieren sich mittlerweile, um die Technologieführerschaft in einzelnen Industriezweigen zu übernehmen (Gallagher 2014).

Dieser globale Wettbewerb führt auch dazu, dass die Politik zunehmend nach Ansätzen sucht, um heimischen Firmen Wettbewerbsvorteile in diesen wachsenden Industriezweigen zu verschaffen. Die Europäische Kommission betont in seiner Wachstumsstrategie, dass die *first mover* Vorteile Europas im Bereich grüner Lösungen durch wichtige Wettbewerber herausgefordert werden, insbesondere aus China und den USA (European Commission 2010, p.14). Die Fragen, die dies aufwirft, haben eine besondere Brisanz, da Umwelttechnologiemärkte in hohem Maße von umweltpolitischen Eingriffen abhängen. Marktschaffende Maßnahmen, wie die Einspeisevergütung für erneuerbare Energien, sind in der Regel die Grundlage für die Entwicklung und Ausbreitung dieser Technologien (Jänicke & Lindemann 2010).

Solche marktschaffenden Maßnahmen werden mittlerweile nicht allein als ein Teilbereich der Umweltpolitik sondern auch als innovations- und industriepolitisches Instrumentarium verstanden. Der Aufbau neuer Umwelttechnologiemärkte wird zunehmend auch als eine Investition für den Aufbau heimischer Wettbewerbsvorteile in entstehenden Industriezweigen gesehen. Gleichzeitig, führt der steigende Wettbewerbsdruck dazu, dass die wirtschaftlichen Argumente einer grünen Industriepolitik zunehmend herausgefordert werden. Im Bereich der Fotovoltaikindustrie wird beispielsweise von Kritikern behauptet, dass deutsche Marktförderung vor allem ausländischen und insbesondere chinesischen Anbietern zu Gute gekommen sei (EFI 2013; BMBF 2011).

Vor diesem Hintergrund geht dieses Dissertationsprojekt folgenden aufeinander aufbauenden Fragen nach:

1. *Wie beeinflussen Entwicklungen in wichtigen Schwellenländern globale Innovationsprozesse und Wettbewerbsdynamiken in politisch geförderten Umwelttechnologiemärkten?*
2. *Was sind die Implikationen dieser globalen Wettbewerbsdynamiken für die Gestaltung und Bewertung von Politik zur Förderung von Innovation im Bereich der Umwelttechnologie bei gleichzeitigem Erhalt nationaler Wettbewerbsfähigkeit?*

Das Dissertationsprojekt besteht aus vier Artikeln. Zwei dieser Artikel adressieren die erste Forschungsfrage (Artikel #1 und #2) und zwei die zweite Forschungsfrage (Artikel #3 und #4). Jedes dieser Paare besteht aus einem vorwiegend konzeptionellen Beitrag (Artikel #1 und #3) und einem vorwiegend empirischen Beitrag zur Literatur (Artikel #3 und #4). Beide empirischen Beiträge werten

[1] Der Begriff Umwelttechnologien im Rahmen dieses Dissertationsprojektes bezieht sich auf die breite Interpretation des Begriffes, die im Aktionsplan für Umwelttechnologie in der Europäischen Union zur Anwendung kommt, und schließt alle Technologien ein, „die umweltverträglicher sind als entsprechende Alternativen“ (European Commission 2004, p. 2).

Entwicklungen im Bereich der Solarenergie, speziell aus dem Fotovoltaiksektor aus. Der Fotovoltaiksektor ist als klassischer Fall eines politisch geförderten Marktes besonders für die Beantwortung der oben genannten Forschungsfragen geeignet. Konzeptionell, baut das Dissertationsprojekt auf bestehende evolutionsökonomische Ansätze aus der Literatur zu Umweltinnovation und technologischem Wandel auf. Insbesondere wird auf Literatur aus diesem Bereich mit Fokus auf Umweltinnovation, nationaler Wettbewerbsfähigkeit und der Rolle von Politik dabei Bezug genommen.

Es folgt eine kurze Zusammenfassung der vier Artikel des Dissertationsprojektes:

Artikel #1: Eine Neubewertung des „lead market" Konzeptes: sein Beitrag zur Umweltinnovationstheorie

In Artikel #1 wird eine kritische Bewertung des *lead market* Konzeptes vorgenommen. Dabei wird insbesondere auf den Beitrag des Konzeptes zur wissenschaftlichen und politischen Diskussion zum Thema Umweltinnovation und Wettbewerbsfähigkeit eingegangen. Es wird festgestellt, dass das *lead market* Konzept den einzigen konzeptionellen Ansatz bietet, um den Einfluss länder-übergreifender Wettbewerbsdynamiken im Rahmen der globalen Ausbreitung von Umweltinnovationen analytisch zu erfassen. Die *lead market* Literatur hat zudem wichtige empirische Evidenz für die globale Diffusion politische geförderter Umwelttechnologiemärkte geliefert. Damit hat es eine wichtige Grundlage für die Hypothese geschaffen, dass eine besonders anspruchsvolle und innovationsfreundliche Umweltpolitik Firmen in den entsprechenden Vorreiterländern sogenannte *early mover* Vorteile verschaffen können.

Gleichzeitig weist der Artikel auch auf eine Reihe von Defiziten des *lead market* Konzeptes hin. Für die Beantwortung der ersten Forschungsfrage dieses Dissertationsprojektes sind zwei Punkte hervorzuheben. Erstens beschränkt sich die Analyse in der bestehenden *lead market* Literatur auf OECD-Länder. Sie geht bisher noch nicht auf die wachsende Rolle von Schwellenländern, insbesondere Chinas, in der Weltwirtschaft allgemein und im Besonderen im Bereich der Umwelttechnologie ein. Zweitens wird in der *lead market* Literatur davon ausgegangen, dass die Diffusion der Nachfrage in der Regel der Globalisierung des Angebots vorausgeht. Der angebotsseitige Wettbewerb *während* der Entstehung eines *lead markets* wird nicht diskutiert. Um diese Lücken zu schließen skizziert der Artikel eine Reihe von Forschungsfragen. Dabei wird insbesondere neue Forschung zu den dynamischen Interdependenzen zwischen *lead* und *lag markets* im Rahmen eines globalen Innovationssystems gefordert. Diesem Fragenkomplex wird dann im Artikel #2 anhand von Entwicklungen im Fotovoltaiksektor nachgegangen.

Artikel #2: Dynamiken eines politisch geförderten Marktes: Ko-Evolution von technologischen Innovationssystemen im Fotovoltaiksektor in Deutschland und China

Ausgehend von dem Konzept eines technologischen Innovationssystems (TIS) wird im Artikel #2 ein Rahmen für die Analyse geographischer Unterschiede und länder-übergreifender Interdependenzen bei der Entwicklung neu entstehender Technologiefelder entwickelt. Kern des Analyserahmens sind die sieben Systemfunktionen zur Analyse von Entwicklungsdynamiken von TIS, die in Hekkert et al. (2007) vorgestellt werden. Darauf aufbauend wird das Konzept asymmetrischer und interdependenter TIS, die sich zeitgleich in einem ko-evolutionären Prozess in unterschiedlichen

Ländern entwickeln, formuliert. Der Begriff der Ko-Evolution wird als Entwicklungsprozess definiert, bei dem zwei Teilsysteme sich wechselseitig in ihrer Entwicklung beeinflussen. Die wechselseitigen Einflüsse zwischen zwei länder-spezifischen TIS werden durch direkte transnationale Verknüpfungen sowie durch indirekte Kanäle, die sich in Form von *spillover*- und Rückkopplungseffekten manifestieren, ermöglicht.

Diese Analyserahmen wird in dem Artikel dann für die Analyse des TIS-Entwicklungsprozesses für den Bereich kristalliner Silizium-basierter Fotovoltaiktechnologien in den Ländern China und Deutschland im Zeitraum von 1999/2000 bis 2010/2011 eingesetzt. Das wichtigste empirische Ergebnis der Analyse ist, dass die Entwicklungsprozesse in Deutschland und China nicht nur Interdependenzen sondern auch wichtige Komplementaritäten im Rahmen eines globalen Entwicklungsprozess aufweisen. Während die Entwicklung in Deutschland der zentrale Treiber der globalen Nachfrage war, stellten die Prozesse in China einen Schlüssel für die Ausweitung des Angebots und der damit verbundenen Reduzierung der Herstellungskosten dar. Es wird festgestellt, dass das Zusammenwirken dieser komplementären Entwicklungsprozesse in besonderem Maße zur Gesamtentwicklung des Sektors beigetragen hat.

Diese empirischen Befunde bestätigen die erwähnte konzeptionelle Weiterentwicklung des TIS Ansatzes und bilden die Grundlage für eine Überarbeitung der *lead-lag market* Annahme in der *lead market* Literatur. Die Fallstudie zum Fotovoltaiksektor kann natürlich nur *einen* alternativen Entwicklungspfad zu dem *lead-lag market* Modell aufzeigen. Es bietet damit aber einen wichtigen Anhaltspunkt für die Erforschung weiterer globaler Entwicklungspfade.

Artikel #3: Auf dem Weg zu einem integrierten Ansatz zur Förderung von Umweltinnovation und wirtschaftlicher Wettbewerbsfähigkeit

Artikel #3 geht der Frage nach, wie eine Politik zur Förderung von Umweltinnovation gleichzeitig zum Erhalt nationaler Wettbewerbsfähigkeit beitragen kann. Der Artikel beginnt mit einem Überblick der Literatur zu innovationsorientierter Umweltpolitik sowohl aus dem Bereich neoklassischer Wirtschaftstheorie als auch dem Bereich der Evolutionsökonomik und den darauf basierenden Ansätzen zur Analyse von Innovation und technologischem Wandel. Diese Ansätze werden im Anschluss mit aktuellen wirtschaftswissenschaftlichen Diskussionen zu wirtschaftlicher Entwicklung und Wachstum verglichen. Der Artikel kommt zu dem Schluss, dass neueste Erkenntnisse aus der Wachstumstheorie und die damit verbundenen wirtschaftspolitischen Implikationen eine zunehmende Kompatibilität mit evolutionsökonomischen Ansätzen einer innovationsorientierten Umweltpolitik aufweisen. In beiden Fällen wird darauf hingewiesen, dass Innovation und technologischer Wandel in hohem Maße vom jeweiligen Länderzusammenhang abhängen. Aus diesem Grund wird auf die Notwendigkeit von flexiblen Politikansätzen hingewiesen, die an den jeweiligen Länderkontext angepasst werden müssen. Zudem erfordert die Entwicklung und Umsetzung solcher Politikansätze – ob zur Unterstützung wirtschaftlicher Entwicklungsprozesse oder zur Förderung von Umwelttechnologien – die gleichen grundsätzlichen Governance Mechanismen. Dies weist auf zunehmende Spielräume für eine Integration dieser Politikbereiche hin.

Die praktische Umsetzung einer solchen integrierten Politik erfordert die explizite Berücksichtigung internationaler Prozesse der Technologieentwicklung und der damit verbundenen Wettbewerbsdynamiken. Der Artikel argumentiert anhand empirischer Beispiele aus dem Bereich der Wind- und Solarenergie, dass eine ambitionierte Umweltpolitik in der Tat Chancen für den

Aufbau langfristiger Wettbewerbsvorteile birgt. Allerdings hängt das Ergebnis von weiteren Einflussfaktoren, wie der bestehenden Wirtschaftsstruktur und der Wettbewerbsfähigkeit heimischer Firmen in unterschiedlichen Segmenten der relevanten Wertschöpfungsketten, ab. Ein integrierter Ansatz zur Förderung von Umweltinnovation und wirtschaftlicher Wettbewerbsfähigkeit, so die Schlussfolgerung des Artikels, sollte mit gezielten Maßnahmen zur Förderung des heimischen Angebots in besonders vielversprechenden Segmenten der Wertschöpfungskette einhergehen. Schließlich hängt die Frage der Wettbewerbsfähigkeit auf Märkten für umweltfreundliche Produkte und Technologien nicht nur von rein ökonomische Faktoren sondern ebenso von der Diffusion relevanter Umweltstandards und –regulierungsansätzen ab. Daher sollte eine integrierte Förderpolitik auch den Ansatz einer Umweltaußenpolitik (Jacob und Bär, 2014) aufgreifen. Eine aktive Förderung des Transfers heimischer Regulierungsmuster kann dabei als Instrument der Exportförderung eingesetzt werden.

Artikel #4: Ein Ansatz zur Bewertung von Politikstrategien zur Förderung von Umwelttechnologien und eine Anwendung am Beispiel der indischen National Solar Mission

Aufbauend auf der in Artikel #3 dargestellten Perspektive wird in Artikel #4 ein detaillierter Analyserahmen zur Bewertung von Politikansätzen zur Förderung von Umwelttechnologien entwickelt. Der Artikel beginnt mit einer Kritik der Literatur zu so genannten *policy mixes*. Die Literatur in diesem Bereich hat eine Reihe generischer Konzepte zur Bewertung eines *policy mix* hervorgebracht, ohne dabei auf die speziellen Herausforderungen einzelner Politikfelder einzugehen. Rayner und Howlett (2009) konstatieren, dass sogenannte *optimal integrated policies* so gestaltet werden sollten, dass mehrere Politikziele in kohärenter Weise verfolgt werden können und der Mix an Politikinstrumenten konsistent ist. Das heißt, die eingesetzten Instrumente sollen sich bei der Erreichung der Politikziele gegenseitig ergänzen. Der Artikel kritisiert das Konzept eines *optimalen policy mix* und den einseitigen Fokus, den die entsprechenden Autoren auf Kohärenz und Konsistenz legen. Stattdessen wird auf die normative Dimension der Politikentwicklung sowie auf die Herausforderung inhärenter Zielkonflikte, die bei der Gestaltung eines *policy mix* zwar berücksichtigt aber nicht notwendigerweise vollständig aufgelöst werden können, hingewiesen.

Im Anschluss dieser kritischen Würdigung wird daher das Konzept einer Politikstrategie als Alternative zum *policy mix* Konzept vorgeschlagen. Basierend auf bestehender Literatur sowie Ergebnissen eines Beratungsprojektes der Policy Assessment Group am Forschungszentrum für Umweltpolitik (FFU) (Jacob et al. 2012) wird eine Politikstrategie anhand der folgenden drei Dimensionen definiert:

- *Strategieinhalt*, bestehend aus Politikzielen und den Politikmaßnahmen zur Erreichung dieser Ziele,
- *Strategieprozess*, bestehend aus dem Prozess der Politikentwicklung, - umsetzung und –anpassung,
- *Strategische Kapazität*, bestehend aus den Kapazitäten, die für Politikentwicklung und -umsetzung sowie für den Prozess des Politiklernens und der Einbindung gesellschaftlicher Akteure notwendig sind.

Dieses generische Strategiekonzept bildet die Basis für die Entwicklung des Analyserahmens zur Bewertung von Strategien zur Förderung von Umwelttechnologien. Ausgehend von ko-evolutionären

Ansätzen zur Analyse von Umweltinnovation und technischem Wandel werden Bewertungskriterien für drei Dimensionen von Strategie aus bestehender Literatur abgeleitet.

Der Analyserahmen wird dann beispielhaft zur Bewertung von Indiens Jawaharlal Nehru National Solar Mission (JNNSM) angewandt. Wichtiges Ergebnis dieser Bewertung ist, dass inhärente Konflikte zwischen Zielen für den kostengünstigen Ausbau des Marktes auf der einen Seite und der Förderung des heimischen Industriestandortes im Bereich der Solarenergie auf der anderen Seite ein wichtiges Hindernis für die erfolgreiche Umsetzung der Strategie darstellen. Zudem unterstützt die Strategie relativ einseitig den Marktausbau, während andere wichtige Funktionen des Innovationssystems, wie die Mobilisierung von Ressourcen sowie Wissensentwicklung und –ausbreitung, vernachlässigt werden. Um diesen Herausforderungen zu begegnen, weist der Artikel auf die wichtige Rolle des Strategieprozesses und den Aufbau strategischer Kapazitäten hin. Insbesondere werden die aktivere Einbindung gesellschaftlicher Akteure im Rahmen des Politikprozesses und die Entwicklung von Kapazitäten für eine angebotsseitige Förderung hervorgehoben.

Der Artikel schließt mit einer Diskussion zu einer weiteren Anwendung sowie den verbleibenden Schwächen des Analyserahmens. Eine zentrale Schwäche des Ansatzes – sowie der Literatur auf der er aufbaut – ist die noch sehr eingeschränkte Auseinandersetzung mit politischen Aspekten bei der Bewertung von Zielkonflikten. Die Entwicklung von Kriterien und Analyseinstrumenten für die Berücksichtigung von politischen Einflussfaktoren bei der Bewertung von Politikstrategien für die Förderung von Umwelttechnologien stellt daher einen wichtigen Bereich für zukünftige Forschung in dem Feld dar. Ein möglicher Ansatz wäre die Durchführung eines systematischen, länder-übergreifenden Vergleichs von Politikstrategien. Dabei wäre auf die Rolle bestehender Governance-Strukturen und politischer Rahmenbedingungen für die Ausgestaltung der Strategien einzugehen. Der Analyserahmen, der in dem Artikel vorgestellt wird, würde eine geeignete Grundlage für ein solches Forschungsvorhaben bieten. In einem weiteren Schritt wäre eine Analyse der wechselseitigen Beeinflussung verschiedener Länderstrategien von großem Interesse. Wie in diesem Dissertationsprojekt dargestellt, gewinnen wechselseitige Einflüsse dieser Art im Bereich neu entstehender Technologiefelder zunehmend an Bedeutung.

1. Introduction

1.1. The global diffusion of environmental technologies as a key to sustainable development

It is widely accepted that sustainable development is dependent on innovation in environmental technologies and their global diffusion. This is particularly true for a number of global environmental problems, such as climate change and growing resource scarcity (IPCC 2014; WBGU 2011). An effective response to these challenges requires not only the rapid development of low-carbon and resource-efficient technologies, but also their accelerated adoption in countries across the globe. This is recognized in the various green economy and green growth concepts promoted internationally by organizations like the World Bank, OECD, UNEP and the European Commission. Despite differences in focus and emphasis, these concepts all share the common understanding that innovation in environmental technologies[2] and their global diffusion represent an important driver for greening economic development around the globe (World Bank 2012; OECD 2011; European Commission 2014; UNEP 2011; Jacob et al. 2014).

At the same time, technological innovation represents a key to sustaining the economic underpinnings of a green economy. As suggested by the concept of ecological modernization, innovation in environmental technologies offers an important entry-point for capturing synergies between environmental policy objectives and economic development. By offering marketable products and services with an improved environmental performance, environmental technologies can help alleviate environmental degradation, while generating income for businesses and their employees (Jänicke 2008). In this vein, the global diffusion of novel environmental technologies not only implies the spread of more environmentally friendly patterns of production and consumption. It also implies the expansion of corresponding market opportunities (Jänicke & Jacob 2004; Jänicke 2012). The dynamic growth of markets for renewable energy technologies represents a powerful example in this regard.

1.2. Policies for promoting markets for environmental technologies in a changing global economy

As demonstrated by numerous empirical examples, the innovation in environmental technologies is highly dependent on policy intervention (Jänicke & Lindemann 2010; Beise & Rennings 2005). Environmental externalities and path-dependencies create lock-in effects, which bias innovation in favor of existing technologies. As a result, policy intervention is required – at least temporarily - to level the playing field between established technologies and new, less polluting technologies and allow new markets to take shape (van den Bergh et al. 2007). Due to their dependence on policy, the related markets are frequently referred to as "policy-driven" (Oosterhuis 2007).

Past research has shown that successful policy approaches have typically involved a mix of policy measures (Jänicke & Lindemann 2010; Gunningham & Grabosky 1998). Targeted public R&D spending and other incentives for technology development are important elements of such a policy

[2] The definition of environmental technologies used in this thesis follows the broad definition proposed in the European Union's Environmental Technologies Action Plan (ETAP) and includes "all technologies who use is less environmentally harmful than relevant alternatives" (European Commission 2004, p. 2).

mix. They are rarely sufficient, however, for stimulating markets for environmental technologies at a significant scale. Equally important for the widespread adoption of environmental technologies are demand-side measures (also known as deployment policies), such as the well-known example of feed-in tariffs for renewable energies (Lewis & Wiser 2007; Hoppmann et al. 2013).

Due to their high financial impact, deployment policies represent a particularly controversial element of such a policy mix (EFI 2014, p.52). As a result, corresponding policy measures have rarely been justified on purely environmental grounds. The promise of economic co-benefits has represented a central argument in favor of ambitious market support for environmental technologies. In Germany, in particular, both researchers and policy makers have argued that pioneering demand-side policies could offer competitive advantages for firms in the domestic market. If successful in stimulating a vibrant national market - so the thinking went - developments would inspire other countries to follow suit and new markets would emerge as the technologies diffused globally. Firms in the so-called "lead market" would then be well positioned to capture significant shares of these potential export markets, thus strengthening the competitiveness of the related industrial sector and the national economy as a whole (Bundesregierung 2007; Bundesregierung 2008; Jänicke & Jacob 2004; European Commission 2006; Porter & van der Linde 1995).

As the vision of a green economy gains increasing traction, the ambition to promote environmental policy objectives along with economic competitiveness are attracting growing interest among policy makers around the globe. In tandem with this, global competition in the field of environmental technologies has increased markedly. Among other things, it is becoming increasingly clear that competition in the field of environmental technologies is no longer restricted to the highly industrialized countries (Gallagher 2014). Until recently, newly industrializing countries were assumed to be laggards when it came to advances in environmental technologies, following the principle of later abatement equals faster abatement equals cheaper abatement (Löschel 2002; del Río González 2008). Recent developments have shown, however, that in a number of areas, China and other emerging economies are positioning themselves to capture leadership positions in these new industries. In the field of renewable energy, China now leads the world in annual investments (Frankfurt School-UNEP Centre/BNEF 2014).

1.3. Central research questions

This changing competitive landscape has important implications for policy makers and researchers in the field. Increased global competition is placing pressure on policy makers to help domestic firms compete in this growing sector of the economy. As pointed out in the European Commission's 2020 growth strategy, Europe's first mover advantages in the field of green solutions are increasingly being challenged by important competitors, most notably the US and China (European Commission 2010, p. 14) In this vein, market support for environmental technologies is increasingly viewed as a strategic element of a new generation of industrial policy rather than merely a subfield within the realm of environmental policy. On the other hand, the growing role of emerging economies and the related competitive pressures are raising new questions regarding the alleged economic benefits of market support policies. Among other things, critics have argued that German market support for solar energy has mainly benefited suppliers abroad, most notably in China (EFI 2013; BMBF 2011).

Against this background, this thesis seeks to answer the following inter-related questions:

1. *How are developments in important emerging economies influencing the global dynamics of innovation and economic competition in policy-driven markets for environmental technologies?*
2. *What are the implications of these global dynamics for the design and assessment of policies aimed at promoting innovation in environmental technologies, while sustaining national competitiveness?*

2. Brief Review of Current Debates in the Literature and Identification of Key Research Objectives

To answer the questions posed above, the thesis builds on the existing literature on environmental innovation and technological change. In particular, it focuses on literature in the field, which discusses the link between environmental innovation and national competitiveness and the role of policy in this context. The following section provides a brief review of the relevant literature and identifies the key gaps, which are addressed by this thesis.

2.1. Environmental innovation and national competitiveness

2.1.1. Lead markets for environmental innovation in a changing world

A key starting point for the discussion on how to balance environmental policy objectives and economic competitiveness is the Porter Hypothesis, as formulated by Porter and van der Linde in the mid-1990s (Porter & van der Linde 1995). They proposed that well-designed environmental policies have the potential to enhance economic competitiveness of domestic firms in two important ways. Firstly, environmental policies may induce innovations that not only help reduce environmental pollution but also enable cost savings via reductions in the consumption of energy or other resources and materials. This case, known as the strong Porter Hypothesis, implies that investments in environmental innovation translate directly into cost reductions and hence increased competitiveness of the corresponding firms. Secondly, successful environmental policies, which anticipate global regulatory trends, can offer domestic firms a so-called early mover advantage. Once similar policies are adopted around the world, firms in the pioneer countries may gain a competitive advantage, due to their head start in developing solutions to fulfill the new regulatory requirements. In other words, even in the absence of immediate cost reductions, this weak version of the Porter Hypothesis offers the promise of a potential link between environmental innovation and competitiveness.

These claims have given rise to a voluminous empirical literature, mostly investigating the strong Porter Hypothesis. This body of literature has focused narrowly on how new regulatory measures have affected the productivity of firms directly affected by the regulation. As such, these studies have mostly been national in scope and have not considered the regulatory context in other countries (Ambec et al. 2013). Only more recent studies have allowed for a time lag between the introduction of regulatory measures and the impact on competitiveness (Lanoie et al. 2008). Overall, the results of these studies have been inconclusive, offering no clear evidence for or against this first part of the Porter Hypothesis.

The weak version of the Porter Hypothesis has given rise to a separate literature on so-called “lead markets” for environmental innovations (Beise & Rennings 2005; Jacob et al. 2005; Jänicke & Jacob

2004).[3] Until recently, the concept of lead markets has represented the only theoretical approach focused explicitly on transnational processes of innovation and diffusion of environmental technologies, while explicitly acknowledging the importance of national boundaries in shaping this process. Based on a series of case studies, the lead markets literature has shown that the early introduction of environmental policy in a selected country may indeed help spur the worldwide diffusion of related environmental technologies. In most cases, the process of technology diffusion from the lead market to the so-called lag markets has been accompanied by a process of environmental policy diffusion (Jacob et al. 2005; Beise & Rennings 2005). Though only one of several factors influencing the global diffusion of environmental innovations, policy instruments have been found to play a pivotal role (SRU 2002)

These empirical findings gave rise to the conclusion among policy makers and researchers alike that anticipatory environmental policy could indeed provide a competitive advantage to the firms in the lead market (Beise et al. 2002; European Commission 2006; European Commission 2007; Bundesregierung 2008). The original literature on lead markets largely failed to discuss, however, under what circumstances policy-induced processes of diffusion would in fact translate into a revealed competitive advantage, i.e. the sustained market success of firms in the lead market. Instead, the implicit assumption was that firms in the lead market would indeed translate their early mover advantage into a lasting competitive advantage and capture important shares of the so-called lag markets. Figure 1 provides a stylized depiction of the policy and market developments, which this assumption implies.[4] As indicated in the diagram, the role of supplier structures in the lag markets are not considered in the lead-lag market model. By excluding a discussion of competing suppliers in the lag market, the original lead market literature failed to consider this crucial factor influencing competitive success.

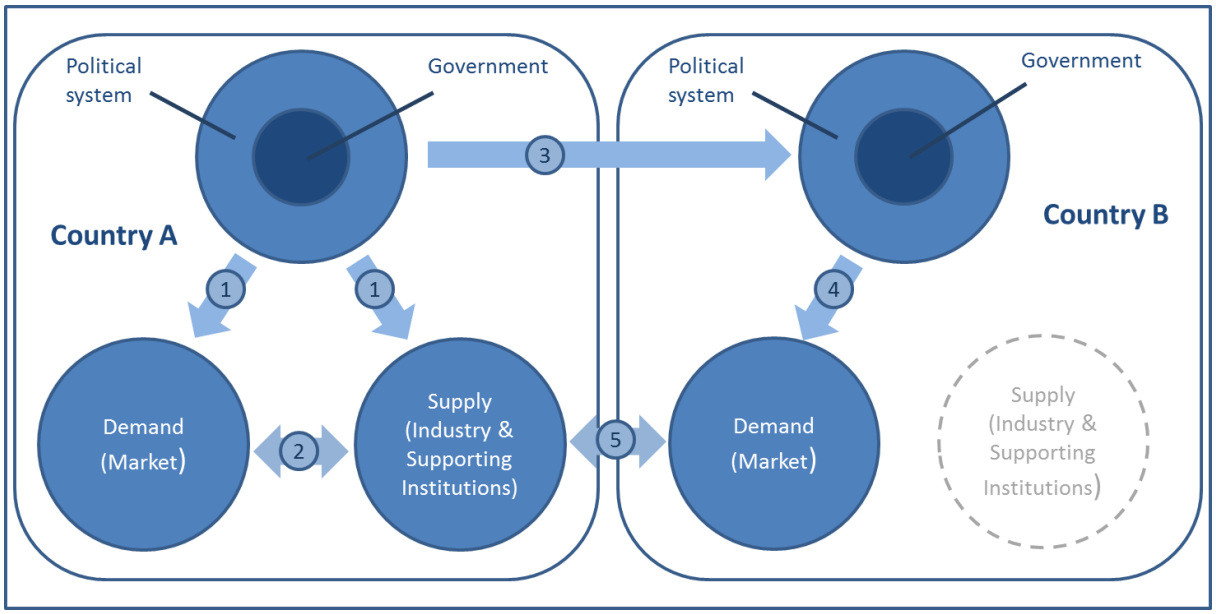
In addition, the original lead market literature has failed to consider the increasing role of emerging economies, in particular China, within the global economy in general and in the field of environmental technologies in particular. In fact, the lead market concept as formulated by Beise explicitly limited itself to the OECD countries (Beise 2006; Beise 2004). Emerging economies were assumed to represent passive recipients of environmental innovations developed in the industrialized countries. Their role as innovators and competitors within an emerging technology field was not considered.

The thesis takes a first step towards addressing these shortcomings in the lead market literature. It offers both conceptual and empirical contributions in this regard.

[3] Paper #1 of this thesis offers a detailed discussion of the lead market concept and how it relates to the broader literature on environmental innovation and technological change.

[4] As indicated above, the process of environmental innovation and diffusion is understood to be a complex process influenced by a number of different factors. Figure 1 offers only schematic representation of key processes within this context and does not claim to be a full representation of the complex relationship, which has been acknowledged in the relationship.

Figure 1: Stylized depiction of policy, market and industry dynamics considered in a lead-lag market model of policy-induced diffusion processes



1. Policy stimulates demand for environmental technologies and supports corresponding research and development;
2. Demand enables expansion of supply; learning on the supply-side enables improved and lower-cost offerings, which reinforce market expansion;
3. Market success stimulates a process of policy diffusion from lead to lag markets;
4. Policy diffusion stimulates demand in lag markets;
5. Market expansion in lag markets provides export opportunities for firms in the lead market

Source: Author's own representation.

2.1.2. The changing geography of innovation and industrial development in emerging environmental technologies

In particular, this thesis offers insights on the changing role of China and other emerging economies and how this is affecting the dynamics of innovation and industrial development in new environmental technology fields. With this, it engages with an emerging debate in the broader literature on environmental innovation and technological change. As Coenen et al. (2012) have pointed out, this literature has been largely blind to the geographic dimensions of the development and diffusion of environmental innovations. They state that the literature still "strongly favors a 'diffusion' model, where innovations are assumed to start in industrialized countries and slowly trickle down the development gradient into emerging and finally developing countries" (Coenen et al. 2012: 971). Recent developments in the field of environmental technologies are posing a fundamental challenge to this model of technological change. As alluded to above, China's rapid rise in the field of renewable energy technologies is calling into question the traditional role of industrializing and emerging economies in these rapidly developing industries (Gallagher 2014).

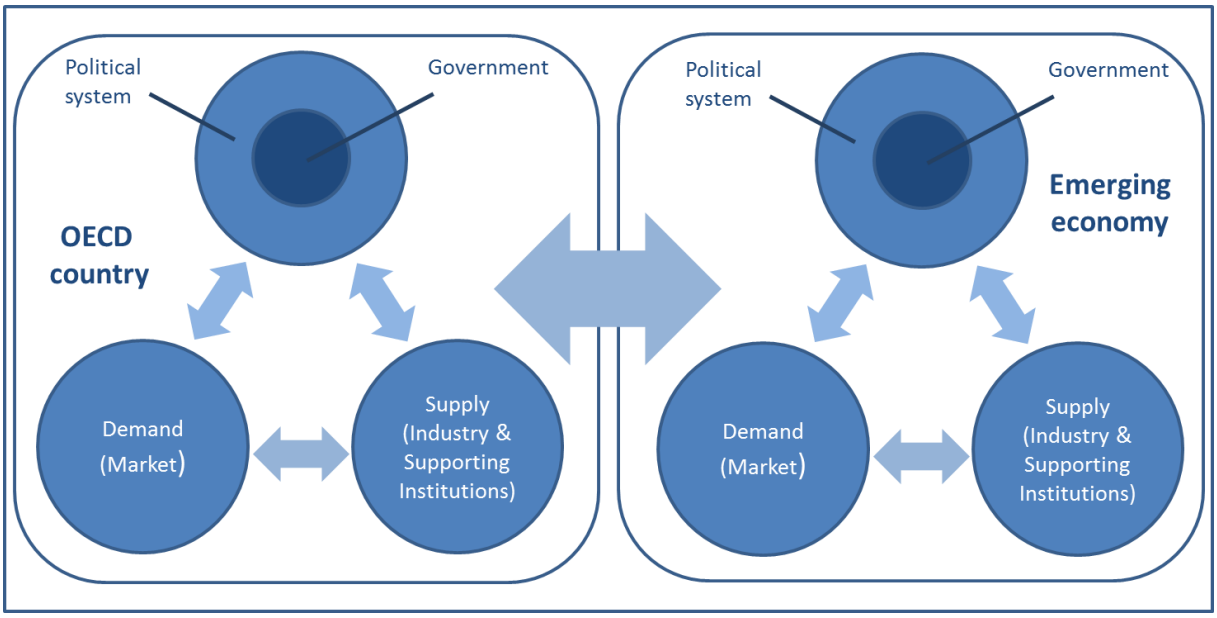
This calls for new analytical approaches that are able to capture these shifts in the geography of environmental innovation. Until recently, the lead market literature represented the only framework in the literature, which placed an explicit focus on geographic aspects. While it represents an important starting point for this discussion, it does not offer an appropriate framework for capturing the changing role of emerging countries in this context. It seeks to explain the global competitive

success of country-specific "innovation designs" (i.e. technological artefacts). It highlights the role of international competition in enabling the global diffusion of particular environmental technologies at the expense of others.

As highlighted in Figure 1 (above), a crucial assumption of the framework is that the global diffusion of *markets* (i.e. demand) for environmental technologies precedes the internationalization of corresponding *industries* (i.e. supply). An increasing number of empirical cases are showing that this linear model of innovation and diffusion no longer reflects reality in a global economy, characterized by the increasing internationalization of global production networks. Moreover, it is precisely in this context that the role of emerging economies, in particular China, is rapidly gaining in importance.

The observation that traditional models of innovation and diffusion do not adequately represent the process of technological development and change are not new (Bell & Pavitt 1993; Metcalfe 1988; Rosenberg 1972; Rosenberg 1976). Bell & Pavitt (1993) have noted that the international diffusion of technology from industrialized to developing countries typically entails both adaptations during the initial adoption of a technology by local industry and incremental improvements throughout its lifetime. Nevertheless, the respective roles of industrialized countries as developers and developing countries as recipients of technology have largely remained intact. Although an increasing number of scholars are addressing the dynamics of environmental innovation and technological change in emerging economies, the related studies continue to frame these developments as processes of catching-up to developments in industrialized countries. As a result, they have focused on how industrialized countries have influenced developing or emerging countries and not vice versa (Binz et al. 2014; Gosens & Lu 2013; Schmidt & Dabur 2013). The concept of environmental leapfrogging, on other hand, has remained mainly at a theoretical level (Watson & Sauter 2011).

Figure 2: Revised depiction of dynamic inter-relationships between policy, market and industry in OECD countries and emerging economies



Source: Author's own representation.

This thesis provides an alternative perspective, focusing particular attention on the mutual interdependencies between industrialized countries and emerging economies (see Figure 2). It contends that, for understanding the global dynamics of environmental innovation and technological

change, it is absolutely crucial to also consider how emerging countries are beginning to shape developments in the industrialized world.

2.2. Policies for promoting environmental innovation in a changing world

2.2.1. The role of government policy for promoting environmental innovation and national competitiveness

Building on this debate on environmental innovation within a changing global economy, this thesis then explores related questions on the role of government policy for the promotion of environmental technologies and its implications for national competitiveness. A review of the debate on this subject reveals that few studies have explicitly tackled this question. As mentioned above, existing studies have mainly focused on empirically testing the static effects of environmental regulation on firm-level productivity, which has yielded inconclusive results (Ambec et al. 2013). These studies ignore the dynamic effects of innovation and technological change on the broader process of economic development and growth.

Meanwhile, mainstream economic theory has made important advances in integrating the dynamic effects of innovation and technological change in models of economic growth (Aghion & Durlauf 2005; Acemoglu 2009). Correspondingly, policy recommendations for promoting economic development and national competitiveness no longer adhere to a former neoliberal agenda of simply "getting the prices right", i.e. minimizing interventions in the market. Rather the emerging consensus is that economic development policy requires a highly context-specific approach, building on national endowment structures (Commission on Growth and Development 2008; Lin 2012). This trend has been further strengthened by the events of the global financial crisis (World Bank 2014; IMF 2009; IMF 2010).

In this vein, paper #3 discusses the evolving mainstream discourse on economic policy and relates it to governance approaches for the promotion of environmental innovation and technological change. On this basis, it explores the scope for integrating an innovation-oriented environmental policy with policies for promoting national competitiveness.

2.2.2. Assessing policies for the promotion of environmental technologies

In a second step, the thesis tackles the more nuanced question of how to *assess* an integrated set of policies aimed at promoting a particular environmental technology sector. To do so, the thesis builds on existing literature on the governance of environmental innovation and technological change. The widespread consensus in this literature is that individual policy measures do not suffice to promote environmental innovation and technological change. Rather it requires a nuanced and flexible approach to policy making based on so-called "policy mixes" (Blazejczak et al. 1999; Hemmelskamp et al. 2000; Klemmer 1999; Jänicke & Jörgens 2004). Although the need for such policy mixes is widely accepted, relatively little work has been done to define more clearly what constitutes an appropriate policy mix for promoting environmental innovation. The existing approaches address particular aspects of this question, but do not attempt to provide a comprehensive framework for assessing or comparing policy mixes for the promotion of environmental innovation.

The term "policy mix" captures the basic understanding that single policy measures are not sufficient for promoting environmental innovation and the related transition to more sustainable systems of

consumption and production. It reflects the basic consensus in this literature that a mix of policy measures from different policy fields are needed to steer innovation and technological change towards the development and diffusion of more sustainable solutions. Hence, it represents an important starting point for the discussion of an integrated policy approach to the promotion of environmental innovation and technological change. However, to date, a more nuanced definition of the concept and what it means for policy making in this context is missing (Rogge & Reichardt 2013). The thesis takes an important step towards closing this gap in the literature and addressing a number of shortcomings of the policy mix concept.

3. Research Case: The Solar Energy Sector

To empirically examine the research objectives outlined above, the thesis focuses primarily on the solar energy sector and, within this sector, on the field of solar photovoltaics (PV). In the following, the main arguments for choosing this empirical case are outlined. More detailed arguments for the specific scope and focus of the case studies that were conducted are not presented here. These can be found in the respective papers.

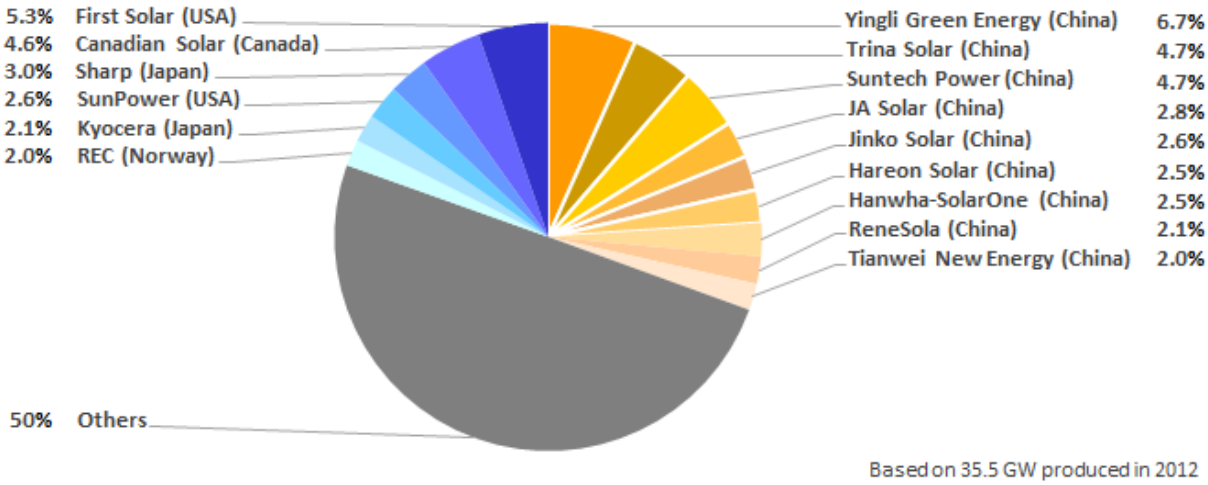
For a number of reasons, the solar PV sector represents a particularly suitable case for investigating both the global dynamics of environmental innovation and diffusion and the related policy questions outlined above. Firstly, the solar energy sector represents an archetypical example of an environmental innovation facing a situation of technology lock-in. On the one hand, it exhibits a large scale potential as a low-carbon energy source. Among the existing clean energy technologies it has the largest technical potential[5] for energy generation (IPCC 2012b, p.12). On the other hand, until recently the cost of solar energy, including energy generated on the basis of solar PV technologies, was still significantly above the wholesale price of electricity on the conventional market. In addition, solar energy faces a cost structure characterized by high initial investment costs and low operating costs. In other words, the large-scale opportunities of solar PV as a low-carbon energy source in the medium to long term are met by short term challenges regarding costs and financing (IPCC 2012a). To overcome these barriers to its widespread adoption, corresponding policy interventions are justified. More importantly, the solar PV sector – along with other renewable energy technologies - has, in fact, been subject to corresponding policy interventions, making it a fruitful case for empirical examination.

Secondly, the solar PV sector and its development trajectory of the past two decades provide ample evidence of the changing global dynamics of environmental innovation and diffusion. In particular, the rapid rise of Chinese firms as leading producers of solar PV cells and modules challenges a number of core assumptions of the lead market literature and related assertions regarding national competitiveness. It provides clear evidence that producers of solar PV modules and cells in Germany have not been able to sustain the early mover advantage conferred on them as firms in the lead market (see Figure 3). Moreover, the role of Chinese firms in reducing the cost of solar PV modules in Germany and elsewhere is key to understanding the global dynamics of the PV sector. China as a major emerging economy has thus played a central role in shaping the development trajectory of the sector. Finally, the important role of China as a supplier of PV technologies was – at least initially -

[5] The physical potential describes the maximum amount of energy generation that is possible considering physical conditions on earth. The technical potential, in contrast, is defined as the amount of energy generation that is possible using existing technologies.

not related to its role as a source of demand (see Figure 4). Hence, the assumption that the diffusion of demand precedes the diffusion of supply – as maintained by the lead market literature – is also clearly refuted.

Figure 3: Market shares of major producers of solar photovoltaic modules

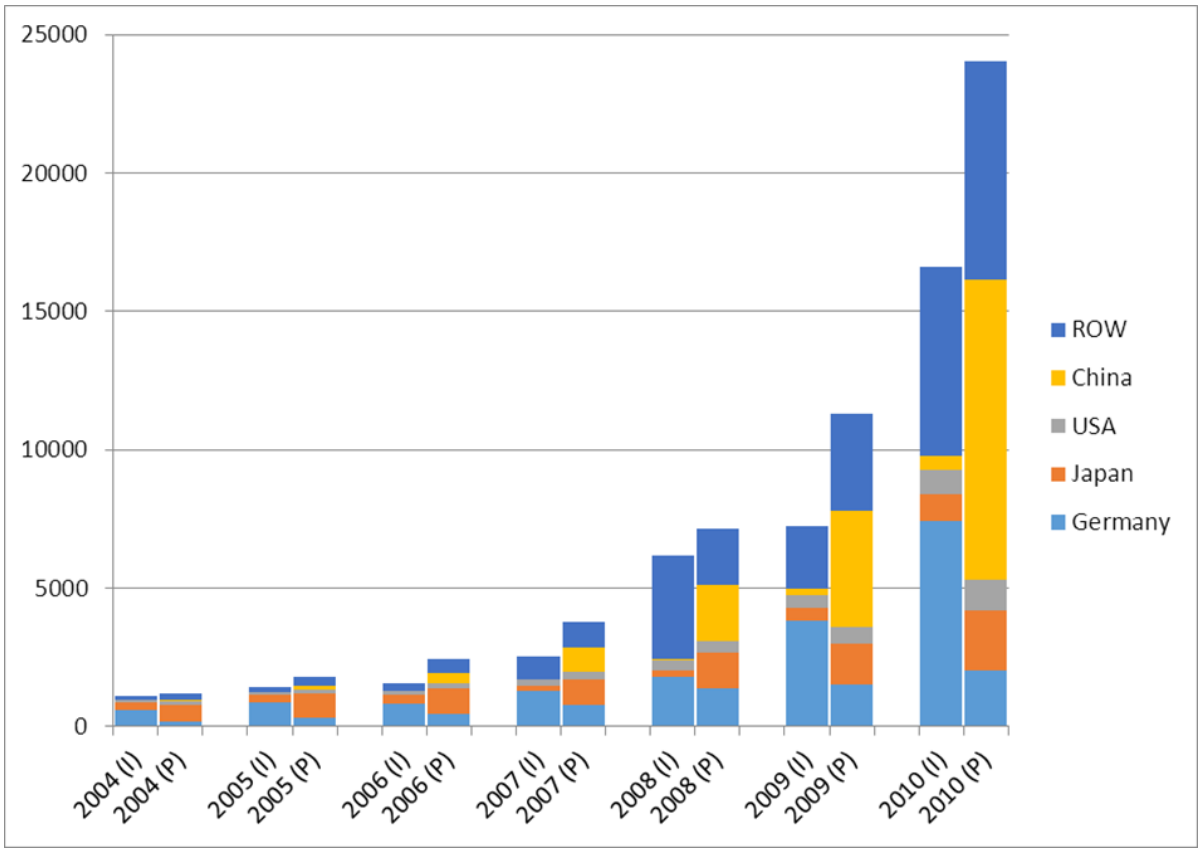


Source: Adapted based on REN 21 (2012), p.48.

Within the solar energy sector, the thesis focuses on developments in Germany, China and India. The first two countries were chosen, due to the pivotal role that these countries have played in shaping developments in the field of solar PV technologies over the past 15 years – the temporal focus of paper #2. During this phase, Germany represented the undisputed lead market and remains - despite the slowdown in annual capacity additions in recent years - the country with the largest share of global installed capacity (REN21 2014). Simultaneously, China has emerged as the global supply leader (see Figure 3 and Figure 4). Correspondingly, developments in China have represented not only the main driver of the geographic reconfiguration of the global production landscape. They have also driven the global build-up of scale economies and related price declines. For this reason, China and Germany were chosen as the two focus countries for the case study on the global dynamics of the solar PV sector.

India was chosen as the empirical case for the application of the policy strategy concept in paper #4. As a major emerging economy with a formal policy strategy in place (i.e. the JNNSM), it is particularly suitable for a first empirical application of the proposed strategy concept. Moreover, as the other major Asian BRIC country and a relative latecomer to the sector, it represents an important contrast to the case of China. Although a formal comparison between China and India based on the strategy concept is beyond the scope of this thesis, the parallel insights that this thesis presents on the two countries provides the basis for a number of tentative conclusions and the formulation of questions for future research. These are presented in paper #4.

Figure 4: Global shares of installed capacity and module production, 2004 - 2010



I: Installed capacity; P: Production of modules
Source: Earth Institute Database.

4. Research methods

The thesis consists of two largely conceptual papers and two papers, which each present the findings from a single, in-depth case study. Thematically the papers represent two pairs including one primarily conceptual and one primarily empirical paper each. The first pair, consisting of Papers #1 and #2, addresses the first research question outlined in section 1.3, while the second pair, consisting of papers #3 and #4, addresses the second research question.

Conceptually, the four papers have in common that they explicitly argue in favor of a dynamic perspective on environmental innovation and technological change. As presented in detail in paper #3, the thesis draws on various streams of literature with a commitment to such a dynamic perspective. They share a common foundation in evolutionary approaches to studying innovation and technological change. Static efficiency criteria found in mainstream approaches to environmental economics and their use in assessing the effects of environmental regulation on innovation and economic competitiveness are rejected (Blind 2010).

The following section briefly outlines the overall rationale of each set of papers and then provides a detailed description of the chosen research method, which was employed in the empirical paper.

4.1. Papers #1 and #2

As outlined above, the first key objective of this thesis is to explore how developments in major emerging economies are influencing global processes of environmental innovation and diffusion. The papers offer both conceptual and empirical contributions in this regard.

Paper #1 offers a detailed critique of the lead market concept and its underlying concepts and assumptions. The paper clearly defines the scope and applicability of the concept in understanding global processes of environmental innovation and diffusion. This conceptual paper serves the purpose of identifying important limitations of the existing lead market concept for addressing the research objectives of the thesis. As outlined in the conclusions of the paper, the fairly limited scope of the lead market concept implies the need for renewed efforts to develop more appropriate concepts and analytical frameworks for capturing the changing global dynamics of environmental innovation and diffusion. In particular, revisions to the linear model of innovation and diffusion underlying the lead market concept are needed.

The task of elaborating such new conceptual approaches is taken up in paper #2. To do so, the thesis builds on the literature on technological innovation systems (TIS) and the related concept of system functions (Bergek et al. 2008; Hekkert et al. 2007). The so-called system functions approach represents a framework for analyzing the dynamics of development and change within a given TIS. Its ability to integrate a dynamic perspective with a systemic view of innovation and technological change in a particular technology field makes it particularly suitable for the analysis of emerging environmental technologies (Coenen & Díaz López 2010). Moreover, in contrast to the lead market concept, it does not assume any particular development path. Rather it offers a framework for capturing how key processes and their interactions shape overall system development.

Until recently, however, studies of TIS development have not explicitly considered the role of geographical factors in influencing TIS dynamics (Coenen et al. 2012). Theoretically, the TIS concept has been defined without reference to geographic boundaries, spanning multiple countries or regions (Carlsson & Stankiewicz 1991). Empirical studies have focused on individual countries or comparisons of countries without addressing interactions between these geographic entities. This lack of an explicit recognition of spatial boundaries and their role in shaping TIS development has been identified as an important gap in the literature (Coenen et al. 2012; Truffer & Coenen 2012). In recent years, a number of scholars have taken steps towards closing this gap by integrating the analysis of TIS functions with concepts from economic geography and related literature on global production networks, technology transfer and transnational entrepreneurship (Binz et al. 2014; Gosens et al. 2014).

This debate on the spatial dimension of TIS developments provides a first conceptual basis for the development of an analytical framework for capturing cross-country inter-dependencies in the development and global diffusion of emerging environmental technologies. As shown in paper #2, it offers a suitable approach for analyzing the co-evolutionary dynamics depicted in Figure 2 above. It frames overall TIS dynamics as a co-evolutionary process of development and change among inter-dependent yet distinct country-level TIS.

The final analytical framework, which is applied for the analysis of the development of the solar energy sector in Germany and China[6] in paper #2, was developed using an inductive case study based approach. This approach is considered appropriate for the following reasons. Paper #1 clearly argues that existing concepts and analytical approaches in the literature do not offer an appropriate basis for capturing the changing global dynamics of environmental innovation and diffusion. In response to this, the aim of the paper is to formulate new, more appropriate concepts. Case studies are considered particularly suitable for this kind of exploratory research (Yin 2008; Eisenhardt 1989). Rather than functioning as evidence for testing an existing hypothesis derived from the literature, the empirical findings of the case study offer the basis for developing new concepts and hypotheses.

As Eisenhardt (1989) points out, this approach has a number of methodological implications for the design and implementation of the case study. Firstly, inductive case studies require a balance between analytical openness (i.e. the lack of an explicit research hypothesis), on the one hand, and the use of analytical constructs to guide the research process, on the other. Secondly, they require an iterative process of comparing the emerging concepts and frames with the evidence being generated from the case. Thirdly, inductive case studies typically involve multiple data collection methods. While methodological parsimony is justified for hypothesis testing, in order to clearly delimit the scope and validity of the resulting findings, inductive case study research benefits from a diversity of data sources to triangulate findings and confirm evolving insights.

These principles were applied as follows for the implementation of the case study methodology for paper #2. In a first step, a case study guide was developed based on the lead market framework and the systems functions approach from the literature on technological innovation systems (TIS). Despite their shortcomings, these frameworks were found to offer the most relevant conceptual foundations for tackling the chosen research objectives. They served as a guide for focusing the data collection and subsequent analysis of the data without defining any preliminary assumptions on the expected findings.

The empirical data collection was then conducted over a period of approximately one year (from mid-2012 to mid-2013), drawing on a wide spectrum of data sources and allowing for multiple rounds of refinement in the development of the resulting conceptual innovations. The data collection began with a thorough review of existing secondary data sources on the development of the solar energy sector globally and in the most relevant countries, including Germany, China, India, the US, Japan and Taiwan. In a second step, a five week research visit to China in the fall of 2012 was conducted to perform a series of interviews, to visit a number of PV production sites (Yingli in Baoding, Suntech in Wuxi and Jiangxi Sornid Hi-Tech Co. in Jiangxi Province) and to attend relevant industry events, such as trade shows, conferences and workshops. During this visit, a total of 21 interviews with experts from industry and industry associations, government, research and international organizations were conducted.

This condensed phase of data collection in China was followed by an iterative process of refining the emerging findings and collecting additional data. This process lasted approximately 8 months and involved 12 additional interviews, participation in several industry events in Germany, visits to two solar research centers, the review of annual reports of major listed PV firms in both Germany and

[6] The choice of country cases has already been addressed above. The more specific temporal and spatial delimitation of each case is discussed in more detail in the individual papers and is not repeated here.

China, the collection of available quantitative data and relevant media reports and other secondary data sources. The aim of this exercise was to enable the triangulation of all important findings derived from interviews and presentations at conferences and other events. This was achieved to a large extent. Only in a few cases, information provided by interviewees could not be confirmed by additional data sources. These cases have been identified in the paper in the form of footnotes.

Finally, a detailed version of the case study results and emerging conceptual conclusions were drafted in the form of a working paper, which was reviewed by both industry experts and fellow researchers (Quitzow 2013). This enabled an additional validation of the empirical data as well as a critical review of the conceptual conclusions. Finally, on this basis, an article for publication was drafted, in which the empirical results were shortened and focused on the task of illustrating the suggested conceptual conclusions. Moreover, the findings were related to the latest discussions in the related literature. This included in particular a review of a number of papers, which were published during the period of data collection on closely related topics. In the course of the peer review process, it was possible to further refine and focus the paper on its key conceptual innovations.

4.2. Papers #3 and #4

As outlined above, the aim of papers #3 and #4 is the development of an approach to assessing and designing policy for the promotion of environmental innovation within the context of a global competitive economy. For this purpose it draws on the same basic conceptual foundation as papers #1 and #2. It assumes a co-evolutionary relationship between policy and environmental innovation and technological change. In other words, the policy making process is both influenced by and exerts an influence on processes of innovation and technological change in economy and society.

On this basis, the two papers develop an explicit analytical perspective for designing and assessing policies for the promotion of environmental innovation in tandem with national competitiveness. In a first step, paper #3 offers a systematic review of arguments for particular policy approaches aimed at the promotion of environmental innovation and contrasts them to evolving policy debates on economic development and competitiveness in the mainstream economics literature. On this basis, it draws a set of conclusions for the design of policies for the promotion of environmental innovation and national competitiveness, while clearly positioning itself within the various analytical perspectives on the topic.

Building on this perspective, paper #4 then develops a framework for assessing policies for the promotion of environmental technologies. Grounded in an explicit analytical perspective on environmental innovation and technological change, it defines a coherent and comprehensive assessment framework.

As a starting point, it takes the discussion on the importance of a policy *mix* for promoting environmental innovation and technological change. As argued in the paper, however, the concept suffers from a number of shortcomings. To overcome these shortcomings, the thesis proposes the concept of a “policy strategy” as an alternative, more realistic framework for assessing and comparing policies for the promotion of environmental technologies. In doing so, it situates this new framework within the discussion on strategy in the field of policy studies. This has its origins in Martin Jänicke’s reflection on ecological and political modernization, in which he has called for “a

policy model that focuses the central state on strategic tasks and transfers detailed regulations more strongly to decentralized actors" (Jänicke, 2009:38). Rather than representing a disillusioned acquiescence to the diminishing role of the State, this was meant as a reconceptualization of the State in more strategic and more flexible terms. He states, "The hierarchical state as an intervention authority legitimized by the whole of society needs to be considered indispensable (see Offe 1987), especially if one seeks to develop a modernization of the industrial system that can effectively balance the immense ecological impacts of global growth." (Jänicke, 2009:38).

Based on these reflections, Jänicke has formulated a strategic approach to environmental policy (Jänicke et al. 2003; Tils 2005). He proposes a departure from a discussion focused on different policy instruments and their relative merits in improving environmental performance. Instead he emphasizes the importance of the entire process of policy development and implementation, beginning with the negotiation of policy goals with relevant stakeholders. He calls for strategies based on precise goals, able to develop and adapt the particular mix of instruments based on the specific context (Jänicke et al. 2003). This discussion has continued within the mainly empirical literature focused on the analysis of the rapidly developing practice of strategy development in the public sector, such as the high-level strategies of the European Union (e.g. Lisbon strategy, EU 2020 strategy, etc.), innovation strategies (e.g. Germany's High Tech Strategy) and strategies for sustainable development, to name a few.

Among these examples, sustainable development strategies have been subject to the most extensive scholarly debate (Steurer & Martinuzzi 2005; Steurer 2007; Quitzow 2011a; Volkery et al. 2006). In the related literature, government strategies are presented as a new form of integrated and adaptive governance, which acknowledges the importance of government in enabling progress towards sustainable development while rejecting the "fiction of centralized state authority" (Beck, 1986: 371). Steurer (2007) proposes that government strategies represent a potential midway between two ideal type positions on the government's role in effecting societal change. On one extreme of the debate lies what they refer to as the planning school in public policy and administration and on the other a purely incrementalist perspective on policy making. According to the former, "complex organizations must plan formally (i) to coordinate their activities, (ii) to ensure that the future is taken into account in today's actions, (iii) to be rational and (iv), to control the use of resources." (Steurer 2007). At the other extreme lies the concept of incrementalism, which holds that policy making evolves "through informal and mutual adjustments among a variety of actors rather than through formalized planning procedures, conducted by distinctive planners." As Steurer (2007) asserts, the former perspective builds on the fallacy that future developments are predetermined, ignoring the uncertainty and unpredictability of future events, while the latter relinquishes any claim to purposeful government action. Hence, government strategies are proposed as a new form of purposeful yet flexible and adaptive governance.

Based on this underlying understanding, the emerging literature on government strategies proposes a number of basic characteristics of a government strategy. In paper #4, this understanding of government strategies and their constituent elements represent the basis for developing an assessment framework for policy strategies aimed at the specific task of promoting environmental technologies. The strategy concept helps frame a synthesis of policy-related findings from the relevant literature on environmental innovation and technological change. These policy-related findings represent the criteria within the proposed policy assessment framework. The final framework, which is presented in paper #4, was derived from an extended version, published in the

form of several working and conference papers (Quitzow 2011b; Quitzow 2011c; Quitzow 2012). It was condensed in an iterative review process, involving discussions with colleagues at the Environmental Policy Research Centre (FFU), a number of reviewers at conferences and workshops as well as three anonymous reviewers who reviewed the paper on the behalf of the journal *Research Policy*.

The aim of this assessment framework is not to conduct an empirical assessment of policy impacts. Due to the multi-facetted nature of both the policy strategy concept and the desired outcome, i.e. the promotion of environmental technologies, a rigorous assessment of policy impacts is not considered feasible and is not the purpose of the framework. Rather, it offers a coherent analytical perspective for evaluating policy *outputs*. This assessment framework is then applied to India's Jawaharlal Nehru National Solar Mission (JNNSM)[7]. This exercise fulfills two parallel functions. Firstly, it fulfills the narrow objective of providing a structured and coherent evaluation of a specific policy strategy, the declared aim of the assessment framework. Secondly, it represents a first empirical test to examine its suitability, scope and limitations for this purpose.

To conduct the empirical assessment, paper #4 draws on publically available qualitative and quantitative data, existing secondary sources as well as interviews, which were conducted as an additional primary data source. Interviews were collected over the course of approximately two years and included three visits to India in October/November 2011, Januray 2012 and March 2013. During these three visits over fifty semi-structured interviews with government officials, industry experts and other stakeholders were conducted. The first visit lasted two months and included stays in Delhi, Ghandinagar (Gujarat), Jaipur (Rajasthan), Pune (Maharashtra), Mumbai and Hyderabad (Andhra Pradesh). As a result, it was possible to interview a broad range of stakeholders at the central level as well as in key Indian states in terms of solar energy policy, i.e. Gujarat, Rajasthan, Maharashtra, Andhra Pradesh. Moreover, it included participation in a number of conferences, including the largest solar energy conference and exhibition in India (SOLARCON).

This first visit was followed by a an iterative process of triangulating and refining the emerging findings based on additional desk-based research and follow-up interviews and discussions with Indian stakeholders and experts during two shorter trips to India in January 2012 and March 2013. The desk-based research included the review of policy documents collected during the research process in India as well as resources available online, including media reports and secondary sources on the JNNSM. In particular, it involved regular monitoring of key media outlets on the Indian solar energy sector, including regular reports issued by Bridge to India (www.bridgetoindia.com) and media reports published on Panchabuta Renewable Energy and Cleantech in India (panchabuta.com). Complementing this ongoing process of data collection, the two additional visits to India were used to close remaining knowledge gaps and discuss and confirm emerging findings with Indian experts.

5. Summary and Key Findings of the Four Papers

The following section provides an extended abstract of each paper, outlining the structure and summarizing the key arguments and findings. While the previous sections have focused on situating each paper within the broader context of the thesis and the research questions it addresses, in this

[7] The choice of country cases has already been addressed above. The more specific temporal and spatial delimitation of each case is discussed in more detail in the individual papers and is not repeated here.

section each paper is presented independently, highlighting its individual narrative and unique contribution.

5.1. Paper #1: The concept of "lead markets" revisited: Contribution to environmental innovation theory

Paper #1 provides a critical review of the lead market concept and discusses its key contributions to the literature on environmental innovation and related policy debates. It begins with an overview of its key theoretical foundations and central policy conclusions on the relationship between environmental innovation and economic competitiveness. After this introduction, the paper discusses the contribution of the lead market concept to the broader literature on environmental innovation. It finds that it offers a unique approach for capturing how the role of cross-country competitive dynamics influences the global diffusion of environmental innovations. Until recently, no other approach in the literature has explicitly tackled the nexus between national and global dynamics in the field of environmental innovation.

While the concept has offered an important starting point for tackling these issues, it is also clear that it suffers from a number of serious weaknesses. Firstly, it builds strongly on the concept of a dominant design, but fails to critically reflect what this implies for the scope of its applicability. Secondly, its discussion of policies and their global diffusion in shaping lead markets is highly simplified. It not only fails to discuss questions of the broader policy *mix* (rather than individual policy instruments) in shaping lead markets, but it also neglects to address how the timing of policy diffusion may influence competitive dynamics between countries. Thirdly, the lead market concept builds on the strong assumption that the global diffusion of demand precedes the globalization of supply in emerging industries. Clearly, this assumption is not (or no longer) valid in all types of industries. Finally, the lead market literature explicitly restricts itself to competition among OECD countries. The implicit assumption, which follows from this, is that emerging markets represent mere recipients of technological innovations developed in the industrialized world.

In particular the last point is being called into question by the dynamic development of the renewable energy sector in China and other emerging economies. This in turn has important implications for the discussion on lead markets for environmental innovation and their links to national competitiveness. To close these important gaps in the literature, the paper outlines a number of questions for further research. Among other things, it calls for research on the dynamic interaction between lead and lag markets within a global system of innovation. It is this question that is taken up in the following paper (Paper #2).

5.2. Paper #2: Dynamics of a Policy-Driven Market: The Co-evolution of Technological Innovation Systems for Solar Photovoltaics in Germany and China

Based on the technological innovation system (TIS) framework and the related system functions approach, paper #2 develops a conceptual framework for analyzing the role of geographical differences and cross-country inter-dependencies in the dynamic development of emerging technology fields. The central pillar of this framework is the set of seven system functions developed by Hekkert et al. (2007) for the analysis of TIS functional dynamics. Adding to this, the paper proposes the concept of asymmetrical yet co-evolving country-level TIS. The concept of co-evolution

is defined as a development process characterized by reciprocal influences between two or more sub-systems. These reciprocal influences in turn are enabled by what is referred to as direct transnational linkages as well as more indirect channels, which manifest themselves in the form of cross-country spillovers and feedbacks.

This conceptual framework is applied for the dynamic analysis of the co-evolutionary process of TIS development in the field of crystalline-based solar PV technologies, focusing on developments in Germany and China between 1999/2000 and 2010/2011. The chosen period represents a time period of particularly dynamic growth in the sector and coincides with a period of German dominance of global demand-side developments. The analysis focuses primarily on the dynamic interactions between Germany and China, as these represented the main driving forces of global TIS development during the time period.

The key empirical finding of the paper is that developments in Germany and China were not only inter-dependent but also highly complementary in enabling the development of the sector. While developments in Germany were crucial drivers of the rapid expansion of demand, the Chinese system of innovation and production represented a key to global supply-side expansion and the resulting cost reductions. It was the combination of these inter-related developments, which enabled the dynamic development of the sector during the time period under consideration.

These empirical findings validate the conceptual framework outlined above and provide the basis for revising the previous lead-lag market assumption. Although the chosen case study can only describe one alternative development pathway to the previous lead-lag market model, it offers a first entry-point for exploring different types of global development trajectories. It not only raises the question which other global development paths are likely but also what factors might influence observed dynamics. In addition, the paper highlights important conceptual implications from the highly uneven process of cost reduction and development of scale economies observed in Germany and China. It points to the importance of cost reduction as a separate system function, which merits attention within the functional analysis of TIS dynamics.

5.3. Paper #3: Towards an integrated approach to promoting environmental innovation and national competitiveness

Paper #3 explores how governments can promote environmental technologies while sustaining national competitiveness. Taking the Porter Hypothesis as its starting point, it briefly reviews the empirical literature on the relationship between environmental regulation and firm competitiveness. It finds these studies to be inconclusive, offering evidence for positive and negative effects from environmental regulation on firm competitiveness. The paper continues by arguing that this focus on firm-specific effects of individual regulatory interventions does not do justice to the complexity of the topic. Firstly, a complete treatment of the question requires an explicit consideration of the *design* of environmental policies. Secondly, it requires a broader, more dynamic perspective on competitiveness. This should encompass not only the polluting sector but also the emergence of new technologies and industrial sectors and how these become competitive at a national and international scale. While a wealth of literature has addressed the role of environmental policy in stimulating innovation and technological change, few studies have explicitly addressed related implications for national competitiveness. The paper makes a unique contribution by offering a systematic assessment of the latter question and drawing related policy conclusions.

To accomplish this, the paper provides a review of the existing literature on innovation-oriented environmental policy, exploring neoclassical approaches and approaches rooted in evolutionary theories of economic development and technological change. The paper finds that neoclassical approaches focused on market failure suffer from similar weaknesses as the literature on environmental regulation and firm competitiveness, focusing on the effects in the polluting sector and failing to take into account important influencing factors, such as complementary policies. Hence policy conclusions remain generic. Evolutionary and system-based approaches, on the other hand, offer a multi-facetted approach to understanding environmental innovation and technological change. Rather than discussing the merits of single policy instruments, these approaches suggest the need for policy mixes tailored to specific sectoral challenges and their evolution over time. This in turn requires corresponding governance mechanisms to enable policy integration and learning and the engagement of stakeholders.

These core elements of evolutionary and system-based approaches to innovation-oriented environmental policy are then contrasted with current debates on the promotion of competitiveness and economic development. The paper finds that recent changes in mainstream debates on economic growth have made the related policy conclusions increasingly compatible with evolutionary approaches to innovation-oriented environmental policy. Both acknowledge that innovation and technological change are highly country-specific processes, which require adaptive policy mixes tailored to the particular innovation system. Moreover, designing and implementing such a policy mix – whether to promote economic competitiveness or more environmentally friendly technologies – requires the same basic set of governance mechanisms. These findings suggest increasing scope for integrating policies for the promotion of environmental innovation and economic competitiveness.

To develop such an approach in practice requires an explicit consideration of the dynamics of international competition and technological change. This dimension is addressed in the final section of the paper, drawing on recent examples from the renewable energy sector. Again it uses the Porter Hypothesis as its starting point. Porter and van der Linde have argued that an innovation-oriented environmental policy can provide early mover advantage to firms in environmental frontrunner countries when they “anticipate and are consistent with international trends” (Porter and van der Linde, 1995: 105). This claim has been proven empirically in the literature on lead markets. In a number of case studies, scholars have shown that the global diffusion of technological innovations is frequently spearheaded by a global process of policy diffusion. Little work has been done, however, to investigate to what extent the related early mover advantages have indeed translated into longer term economic success.

Recent examples from the German wind and solar sectors reveal that in spite of a similar set of frontrunner policies, the resulting dynamics of industrial development and competitiveness have varied significantly. While the competitive advantage of German solar module suppliers was rapidly eroded by the entry of Chinese and other Asian suppliers, German (as well as Danish) wind turbine manufacturers have been significantly more successful at defending global market shares (REN21 2014; REN21 2013; REN21 2012; REN21 2011). Simultaneously, German manufacturers of production equipment have defended their leadership position in the field of solar photovoltaics (Wessendorf 2012).

This empirical case suggests that early mover advantages derived from frontrunner policies do offer opportunities for building longer term competitive advantage. However, the particular outcome depends on additional factors, like the domestic endowment structure and the ability of domestic firms to compete in particular segments of the supply chain. An integrated approach to promoting environmental innovation and national competitiveness, the paper concludes, should combine policies to enable environmental innovation with targeted supply-side measures to support the most promising segments of the emerging supply chain.

Finally, competition in markets for environmentally-friendly products and technologies is not only a matter of economic competition but depends also on the diffusion of the related standards and regulatory solutions. Hence, a further element of an integrated approach to environmental innovation and national competitiveness is captured in the concept of an "environmental foreign policy" (Jacob & Bär 2014). An active promotion of the transfer of domestic regulatory frameworks can serve as a vehicle for encouraging related technology exports. A successful environmental foreign policy in turn is likely to build on areas of domestic environmental policy with particularly ambitious goals or of particular importance domestically.

5.4. Paper #4: Assessing policy strategies for the promotion of environmental technologies: A review of India's National Solar Mission

There is widespread consensus that no individual policy instrument but rather a "policy mix" is needed to effectively drive the development and diffusion of environmental technologies. However, what exactly constitutes such a policy mix remains largely undefined. Paper #4 takes this discussion a step further by developing a comprehensive approach to assessing and designing policy approaches for the promotion of environmental technologies.

The paper begins with a critical review of the literature on policy mixes and related approaches for their assessment. It finds that the existing literature has defined a number of generic concepts for assessing the suitability of policy mixes, which are unrelated to any particular policy field. Rayner and Howlett (2009) state that so-called "optimal integrated policies" require a policy design "in which multiple policy goals can be coherently pursued at the same time, and second, policy instrument mixes are consistent in the sense of being mutually supportive in the pursuit of policy goals" (p.100). The paper challenges the concept of an optimal policy mix and its emphasis on coherence and consistency as central assessment criteria. Instead it highlights the normative dimension of policy making and the need to balance inherent policy trade-offs within a given policy mix. This implies that alternative approaches for tackling a common policy challenge may yield a host of different solutions or *strategies*.

On this basis, the concept of a *policy strategy* is proposed as an alternative to the existing policy mix concept. The relevance of the term is further underlined by the increasing use of formalized strategies in government practice. Drawing on existing literature as well advisory work conducted for the German Ministry of the Environment by the Policy Assessment Group at the Environmental Policy Research Centre (Jacob et al. 2012), a policy strategy is defined as the combination of the following three elements:

- *Strategy content*, composed of policy objectives and the measures designed to achieve them;

- *Strategy process*, encompassing the process of policy development, implementation and adaptation;
- *Strategic capacity*, including the capacities need for policy development, implementation and learning as well as the engagement of stakeholders.

This generic strategy concept represents the basis for the subsequent development of a framework for the assessment of strategies for promoting environmental technologies. Building on a co-evolutionary perspective on environmental innovation and technological change, detailed assessment criteria for each of the elements are derived from the literature on innovation-oriented environmental policy, sustainability transitions and system-based approaches to innovation policy. The resulting assessment framework is summarized in the following table (Table 1).

Table 1: Summary of the assessment framework

Strategy element	Assessment criteria
Strategy content	***Policy objectives*** • Trade-offs and synergies across objectives • Level of ambition and credibility of objectives ***Policy measures*** • Synergies and trade-offs between policy measures within the scope of the strategy • Trade-offs in the design of demand-side policies - Needed stringency of regulatory measures or level of support in financial incentives to enable development of target sector *versus* considerations to avoid unjustified economic rents - Flexibility in terms of technological choice *versus* differentiation in terms of actors and sectors - Predictability *versus* adaptability • Comprehensiveness in terms of supporting weak system functions • Consideration of time-strategic dimension • Consideration of international dimension
Strategy process	• Monitoring and review to facilitate policy learning • Stakeholder engagement to build legitimacy, access knowledge and engage in vision-building to align expectations and anticipate future developments • Horizontal and vertical coordination of actors within the policy sub-system
Strategic capacity	• Match between strategy content and existing governance capacities • Development of governance capacities needed to meet medium- to long-term objectives • Capacities for horizontal and vertical policy coordination • Capacities for accessing knowledge and engaging stakeholders, such as networks of strategic intelligence and private-public interfaces • Accountability mechanisms to avoid capture by private sector stakeholders

Next, the assessment framework is applied in an exemplary fashion to India's Jawaharlal Nehru National Solar Mission (JNNSM). Since a full assessment of the JNNSM is beyond the scope of the paper, the main purpose is to illustrate the value-added of the framework focusing on central features of the JNNSM. Two main results emerge from the assessment. Firstly, an unresolved trade-off between demand- and supply-side objectives is hampering implementation of the strategy. Secondly, strong market support has come at the expense of measures to support other important

system functions, such as the mobilization of resources and knowledge development and diffusion. To tackle both issues, the paper highlights the importance of *process* and *capacity* considerations. While political factors justify the inclusion of supply-side targets in the JNNSM, the development of a suitable approach requires a more active engagement of stakeholders and the development of needed capacities for implementing effective supply-side measures. Similarly, a more comprehensive support strategy – beyond market support - would require increased efforts to enable policy coordination and the development of relevant implementation capacity. This integrated perspective, encompassing all three elements of the strategy concept as well as their inter-relationships, is considered an important value-added of the assessment framework and a key to addressing existing trade-offs.

A remaining weakness of the framework - as well as the underlying literature - is the lack of explicit criteria for considering the political dimension of policy trade-offs. The development of criteria and analytical tools for incorporating political factors in policy strategies for promoting environmental technologies represents an important avenue for future research. One important step in this direction might be the systematic cross-country comparison of policy strategies and how these are embedded and shaped by country-specific governance mechanisms and political conditions. The proposed strategy concept offers an analytical framework for conducting such comparative analyses. In a further step, such an analysis might address the interplay between different country-level strategies, an issue of increasing importance within the context of emerging technology fields.

6. Key Conclusions and Questions for Future Research

Having outlined each paper and its unique contribution to the literature, this final section now returns to the broader contribution of the thesis to the research questions outlined in section 1.3:

1. *How are developments in important emerging economies influencing the global dynamics of innovation and economic competition in policy-driven markets for environmental technologies?*
2. *What are the implications of these global dynamics for the design and assessment of policies aimed at promoting innovation in environmental technologies, while sustaining national competitiveness?*

In the following, central findings and key questions for future research in these two areas are highlighted. Rather than repeating more detailed findings, which are already captured in the individual papers, this section offers a synthesis of the key findings and conceptual contributions of this thesis.

6.1. Dynamic inter-dependencies between industrialized and emerging countries in emerging environmental technology fields

The central contribution of this thesis in answering the first of the two research questions has been to challenge the model of innovation followed by diffusion, which has informed the debate on the global dynamics of environmental innovation and technological change in the past. As the thesis argues, this underlying assumption has led to an outdated understanding of how policy-driven lead markets might influence national competitiveness in the corresponding countries. By assuming a linear process of lead market development followed by diffusion to the remaining lag markets, this

model fails to capture increasing supply-side competition during early stages of lead market development. The importance of international supply-side competition throughout the development of Germany's lead market for solar PV is clearly demonstrated by the thesis.

The findings go a step further than this basic insight, however. Paper #2 shows that Chinese supply-side dynamics were in fact a key enabling factor for the acceleration of market growth in Germany. The thesis, therefore, contends that international market and industry development in emerging environmental technologies are strongly influenced by two parallel phenomena. Firstly, global development dynamics are characterized by spatially defined asymmetries in industrialized and emerging economies. In this case, vigorous and relatively stable demand growth represented a defining feature of German developments, while Chinese dynamics were characterized by exuberant investments in supply-side capacity. Secondly, these asymmetrical developments are inter-dependent and – in this particular case - mutually reinforcing.

With this, the thesis replaces the lead-lag market concept with a concept of co-evolution between national or other spatially-distinct entities. In doing so, it debunks the outdated notion – explicit or implicit – of industrialized countries as the sources and emerging and developing countries as the recipients in the global diffusion of technologies and knowledge. Instead the paper proposes the concept of co-evolving, country-level dynamics, in which uneven developments in industrialized and emerging economies play complementary as well as competing roles.

This represents a fundamental reformulation of the assumed relationship between industrialized and emerging economies in the process of environmental innovation and technological change and offers the starting point for developing a broad spectrum of future research. One important avenue for future research might focus on the comparative analysis of global development trajectories in the field of emerging environmental technologies. In a first step this would entail the identification of different types of global development pathways, the different roles assumed by emerging and industrialized countries and the different modes of interaction and exchange in this context. In a second step, the question could be raised what factors explain the difference between the identified pathways. In addition, this analysis could be linked with a more explicit assessment of the underlying global production networks and their changing spatial configuration and modes of governance. The first elements of such a research agenda have been proposed by Yeung & Coe (2014), who call for a dynamic theory of global production networks. The findings emerging from this thesis represent an important input to such a theory.

6.2. Governing environmental innovation in a competitive global economy

As outlined in the previous section, a first key contribution of this thesis has been the development of a new analytical perspective for understanding environmental innovation within a changing global economy. The second major contribution is the development of a corresponding framework for designing and assessing policies for promoting environmental technologies. In doing so, the thesis takes an important step beyond the existing concept of a policy mix, addressing key shortcomings of the concept. To date, this has represented the overarching policy-related concept cited in the literature on environmental innovation and technological change. Definitions, however, remain vague and are not specific to the policy field.

To replace this vaguely defined concept, this thesis introduces a clearly articulated concept of policy strategy. This serves as the basis for elaborating a framework for policy assessment, which is tailored to the policy field. To accomplish this, the thesis elaborates a detailed set of criteria, derived from existing literature on the role of policies for promoting environmental innovation and technological change. These are then integrated within the framework offered by the policy strategy concept. Hence, a first important achievement is the integration of research findings in the field into one coherent and comprehensive policy assessment framework.

In addition, the policy strategy concept addresses important conceptual shortcomings of the policy mix concept. Firstly, it adds a dynamic dimension to the assessment of policy, which is not considered as an explicit assessment criterion in the policy mix literature. The findings outlined in 6.1 constitute ample evidence that such a dynamic, co-evolutionary perspective on policy and innovation is key to understanding international processes of environmental innovation and diffusion. Paper #3 provides a corresponding argument for the realm of policy development. Among other things, it points out that the mainstream debate on economic development policy has already moved to a more dynamic, innovation-based perspective. In this context, country-specific endowments represent the basis for a process-oriented approach to policy-making, in which government and relevant stakeholders engage in a constructive dialog on context-specific policy approaches. This shift in the economic development policy debate is highly compatible with the dynamic perspective on environmental innovation and technological change proposed by this thesis. Hence a key conclusion of paper #3 is that policies to promote economic competitiveness are also compatible and can be integrated with policy approaches for promoting environmental innovation and technological change. In this vein, this process-oriented perspective to policy-making is also captured in the integrated policy strategy concept, which incorporates the design and management of the policy process as a core dimension of policy assessment.

Secondly, the thesis challenges the focus of existing policy mix concepts on the role of policy coherence. While a high level of coherence within a selected policy domain has important benefits, the thesis posits that this represents an abstract and ultimately unattainable ideal. This is particularly relevant in the dynamic field of environmental innovation and technological change. Policies aimed at promoting potentially disruptive environmental technologies frequently challenge incumbent governance regimes and the technological systems they support and enable. Hence, they may explicitly seek to introduce a degree of incoherence into an established system and aim to unleash a dynamic process of innovation and technological change. This insight helps shift the focus of policy assessment from the aim of achieving coherence across a set of policy objectives and measures to the challenge of setting priorities across different, inherently conflicting policy goals. The empirical case – India's National Solar Mission – clearly demonstrates the importance of this perspective. In particular, it highlights the challenge of addressing trade-offs between the cost efficiency of demand-side measures and the pursuit of politically important supply-side objectives.

Finally, the policy strategy concept captures the insight that individual governments have only limited capacities of their own to effect far-reaching processes of environmental innovation and technological change. Hence, it places governments – the initiators of policy strategies - within a broader context of multi-level governance and innovation systems. From this perspective, policy strategies represent vehicles for stimulating dynamic and mutually reinforcing processes of change. While the concept of multi-level governance is not new (Stephenson 2013), such a dynamic, multi-

level perspective on innovation governance remains poorly developed both in theory and in practice (Kaiser & Prange 2004; Kaiser & Prange 2005; Prange 2008).

Though only briefly touched upon in the empirical analysis of the JNNSM, the concept of policy strategy represents a potential starting point for a research agenda on this topic. It offers a coherent approach for the assessment and cross-country comparison of sector-level governance arrangements, embedded in such a multi-level system of governance and innovation. Existing literature has addressed topics like policy diffusion and convergence (Heichel et al. 2005; Holzinger et al. 2007), the harmonization of regulatory regimes (Eberlein & Grande 2005), vertical policy integration (Lafferty & Hovden 2003; Jacob & Volkery 2004), and regulatory competition (Holzinger et al. 2008). Less emphasis has been placed on more complex dynamics involving experimentation, learning, adaptation, and reinforcement across different geographic entities and different geographic levels. While first contributions exist for the field of climate policy (Jänicke 2013; Jörgensen 2012; Rabe, Roman, and Dobelis 2006; Rabe 2008; Schreurs and Tiberghien 2007), similar analyses for the domain of environmental innovation and technological change are still outstanding.

Applying the policy strategy concept for this purpose promises important empirical insights on how governments are leveraging the dynamics of multi-level reinforcement in environmental innovation policy. In particular, it might explore the role of policy *incoherence* as a driver of dynamic processes of environmental innovation and technological change.

7. References

Acemoglu, D., 2009. *Introduction to Modern Economic Growth*, Princeton, NJ: Princeton University Press.

Aghion, P. & Durlauf, S. eds., 2005. *Handbook of Economic Growth*, Amsterdam: Elsevier B.V.

Ambec, S. Cohen, M., Elgie, S., Lanoie, P. , 2013. The Porter Hypothesis at 20: Can Environmental Regulation Enhance Innovation and Competitiveness? *Review of Environmental Economics and Policy*, 0(0), pp.1–22.

Beck, U., 1986. *Risikogesellschaft. Auf dem Weg in eine andere Moderne*, Frankfurt a.M.: Suhrkamp.

Beise, M., 2006. *Die Lead-Markt Strategie: Das Geheimnis weltweit erfolgreicher Innovationen*, Heidelberg: Springer.

Beise, M., 2004. Lead markets: country-specific drivers of the global diffusion of innovations. *Research Policy*, 33(6-7), pp.997–1018.

Beise, M., Cleff, T., Heneric, O., Rammer, C., 2002. *Lead Markt Deutschland: Zur Position Deutschlands als führender Absatzmarkt für Innovationen*, Mannheim: Zentrum für Europäische Wirtschaftsforschung.

Beise, M. & Rennings, K., 2005. Lead markets and regulation: a framework for analyzing the international diffusion of environmental innovations. *Ecological Economics*, 52(1), pp.5–17.

Bell, M. & Pavitt, K., 1993. Technological Accumulation and Industrial Growth: Contrasts Between Developed and Developing Countries. *Industrial and Corporate Change*, 2(2), pp.157–210.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy*, 37(3), pp.407–429.

Van den Bergh, J. Faber, A., Idenburg, A., Oosterhuis, F. , 2007. *Evolutionary Economics and Environmental Policy. Survival of the Greenest*, Cheltenham, UK: Edward Elgar.

Binz, C., Truffer, B. & Coenen, L., 2014. Why space matters in technological innovation systems: Mapping global knowledge dynamics of membrane bioreactor technology. *Research Policy*, 43(1), pp.138–155.

Blazejczak, J., Edler, D., Hemmelskamp, J., Jänicke, M., 1999. Umweltpolitik und Innovation: Politikmuster und Innovationswirkungen im internationalen Vergleich. *Zeitschrift für Umweltpolitik & Umweltrecht*, 22(1), pp.1–32.

Blind, K., 2010. The Use of the Regulatory Framework for Innovation Policy. In R. Smits, S. Kuhlmann, & P. Shapira, eds. *The Theory and Practice of Innovation Policy. An International Research Handbook*. Cheltenham, UK: Edward Elgar, pp. 217–246.

BMBF, 2011. *Wettbewerbsfähiger durch Leitmarktstrategie?, Dokumentation des BMBF-Workshop vom 7. April 2011*,

Bundesregierung, 2007. *Die Begründung der Bundesregierung für ihren Gesetzentwurf für das Erneuerbare-Energien-Gesetz (EEG) vom 5. Dezember 2007*, Berlin: Bundestags-Drucksache.

Bundesregierung, 2008. *Unterrichtung durch die Bundesregierung Masterplan Umwelttechnologien (Drucksache 16/11322)*, Berlin: Deutscher Bundestag.

Carlsson, B. & Stankiewicz, 1991. Nature, function and composition of technological systems. *Journal of Evolutionary Economics*, 1(2), pp.93–118.

Coenen, L., Benneworth, P. & Truffer, B., 2012. Toward a spatial perspective on sustainability transitions. *Research Policy*, 41(6), pp.968–979.

Coenen, L. & Díaz López, F.J., 2010. Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities. *Journal of Cleaner Production*, 18(12), pp.1149–1160.

Commission on Growth and Development, 2008. *The Growth Report: Strategies for Sustained Growth and Inclusive Development*, Washington, D.C.: World Bank.

Eberlein, B. & Grande, E., 2005. Beyond delegation: transnational regulatory regimes and the EU regulatory state. *2Journal of European Public Policy*, 12(1), pp.89–112.

EFI, 2013. *Gutachten zu Forschung, Innovation und technologischer Leistungsfähigkeit Deutschlands* Expertenko., Berlin.

EFI, 2014. *Gutachten zu Forschung, Innovation und technologischer Leistungsfähigkeit Deutschlands*, Berlin: Expertenkommission Forschung und Innovation.

Eisenhardt, K., 1989. Building Theories from Case Study Research. *The Academy of 1Management Review*, 14(4), pp.532–550.

European Commission, 2010. *Europe 2020: A strategy for smart, sustainable and inclusive growth*,

European Commission, 2006. *European competitiveness report 2006*, Brussels: European Communities (COM(2006) 697 final).

European Commission, 2007. *Explanatory Paper on the European Lead Market Approach: Methodology and Rationale (Annex II to COM(2007) 860 final)*,

European Commission, 2004. *Stimulating Technologies for Sustainable Development: An Environmental Technologies Action Plan for the European Union*, Brussels: European Commission, COM(2004) 38 final.

European Commission, 2014. *Taking stock of the Europe 2020 strategy for smart, sustainable and inclusive growth*, Brussels: Communication from the Commission to the European Parliament, the Council, the European Social and Economic Council and the Committee of the Regions (COM(2014) 130 final/2).

Frankfurt School-UNEP Centre/BNEF, 2014. *Global Trends in Renewable Energy Investment 2014*, Frankfurt a.M.

Gallagher, K.S., 2014. *The Globalization of Clean Energy Technology: Lessons from China*, Boston: MIT Press.

Gosens, J. & Lu, Y., 2013. From lagging to leading? Technological innovation systems in emerging economies and the case of Chinese wind power. *Energy Policy*, 60, pp.234–250.

Gosens, J., Lu, Y. & Coenen, L., 2014. The role of transnational dimensions in emerging economy Technological Innovation Systems for clean-tech. *Journal of Cleaner Production*, in press.

Gunningham, N. & Grabosky, P., 1998. *Smart Regulation: Designing Environmental Policy*, New York: Oxford University Press.

Heichel, S., Pape, J. & Sommerer, T., 2005. Is there convergence in convergence research? An overview of empirical studies on policy convergence. *Journal of European Public Policy*, 12(5), pp.817–840.

Hekkert, M.P., Suurs, R.A.A., Negro, S.O., Kuhlmann, S., Smits, R.E.H.M., 2007. Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change*, 74(4), pp.413–432.

Hemmelskamp, J., Rennings, K. & Leone, F., 2000. *Innovation-Oriented Environmental Regulation. Theoretical Approaches and Empirical Analysis*, Heidelberg: Physica-Verlag.

Holzinger, K., Jörgens, H. & Knill, C. eds., 2007. *Transfer, Diffusion und Konvergenz von Politiken*, Wiesbaden: VS Verlag für Sozialwissenschaften.

Holzinger, K., Knill, C. & Sommerer, T., 2008. Environmental Policy Convergence: The Impact of International Harmonization, Transnational Communication, and Regulatory Competition. *International Organization*, 62(4), pp.553–587.

Hoppmann J., Peters M., Schneider M., H.V.H., 2013. The Two Faces of Market Support – How Deployment Policies Affect Technological Exploration and Exploitation in the Solar Photovoltaic Industry. *Research Policy*, 4, pp.989–1003.

IMF, 2009. *World Economic Outlook 2009: Sustaining the Recovery*, Washington, D.C.: International Monetary Fund (IMF).

IMF, 2010. *World Economic Outlook 2010: Rebalancing Growth*, Washington, D.C.: International Monetary Fund (IMF).

IPCC, 2012a. Chapter 3: Direct Solar Energy. In *Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press, pp. 333–400.

IPCC, 2014. *Climate Change 2014: Mitigation of Climate Change*, Cambridge, UK: Cambridge University Press.

IPCC, 2012b. *Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK: Cambridge University Press.

Jacob, K. et al., 2005. *Lead Markets for Environmental Innovations*, Heidelberg: Physika-Verlag.

Jacob, K. & Bär, H., 2014. Exportförderung innovativer Umwelttechnologien durch den Transfer von Umweltpolitik. *FFU Report 02-2014*.

Jacob, K., Münch, L. & Büttner, H., 2012. *Leitfaden zur Strategieentwicklung im BMU*, Report prepared for the German Ministry of Environment under contract Nr.FKZ UM 09 11 156-3.

Jacob, K., Quitzow, R. & Bär, H., 2014. *Green Jobs: Beschäftigungswirkung einer Green Economy*, Eschborn: Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung.

Jacob, K. & Volkery, A., 2004. Institutions and Instruments for Government Self-Regulation: Environmental Policy Integration in a Cross-Country Perspective. *Journal of Comparative Policy Analysis: Research and Practice*, 6(3), pp.291–309.

Jänicke, M., 2013. Accelerators of Global Energy Transition: Horizontal and Vertical Reinforcement in Multi-Level Climate Governance. *IASS Working Paper*, December.

Jänicke, M., 2012. Dynamic governance of clean-energy markets: how technical innovation could accelerate climate policies. *Journal of Cleaner Production*, 22(1), pp.50–59.

Jänicke, M., 2008. Ecological modernisation: new perspectives. *Journal of Cleaner Production*, 16, pp.557 – 565.

Jänicke, M., 2009. On Ecological and Political Modernization. In A. Mol & G. Spaargaren, eds. *The Modernisation Reader. Environmental Reform in Theory and Practice*. New York: Routledge, pp. 28–41.

Jänicke, M. & Jacob, K., 2004. Lead markets for environmental innovations: a new role for the nation state. *Global Environmental Politics*, 4(1), pp.29–47.

Jänicke, M. & Jörgens, H., 2004. Neue Steuerungskonzepte in der Umweltpolitik. *Zeitschrift für Umweltpolitik & Umweltrecht*, 27(3), pp.297 – 348.

Jänicke, M., Kunig, P. & Stitzel, M., 2003. *Umweltpolitik*, Bonn: Dietz Verlag.

Jänicke, M. & Lindemann, S., 2010. Governing environmental innovations. *Environmental Politics*, 19(1), pp.127–141.

Jörgensen, K., 2012. The role of the state laboratories in multi-level climate policy research: considering India. *FFU Report 04-2012*.

Kaiser, R. & Prange, H., 2004. Managing diversity in a system of multi-level governance: the open method of co-ordination in innovation policy Managing diversity in a system of multi-level governance: the open method of co-ordination in innovation policy. *Journal of European Public Policy*, 11(2), pp.249–266.

Kaiser, R. & Prange, H., 2005. Missing the Lisbon Target? Multi-Level Innovation and EU Policy Coordination. *Journal of Public Policy*, 25(2), pp.241–263.

Klemmer, P., 1999. *Innovation and the Environment*, Berlin: Analytica.

Lafferty, W. & Hovden, E., 2003. Environmental policy integration: towards an analytical framework. *Global Environmental Politics*, 12(3), pp.1–22.

Lanoie, P., Patry, M. & Lajeunesse, R., 2008. Environmental Regulation and Productivity. Testing the Porter Hypothesis. *Journal of Productivity Analysis*, 30(2), pp.121–128.

Lewis, J. & Wiser, R., 2007. Fostering a renewable energy technology industry: An international comparison of wind industry policy support mechanisms. *Energy Policy*, 35(3), pp.1844–1857.

Lin, J.Y., 2012. *New Structural Economics: A Framework for Rethinking Development Policy*, Washington, DC: The World Bank.

Löschel, A., 2002. Technological change in economic models of environmental policy: a survey. *Ecological Economics*, 43(2-3), pp.105–126.

Metcalfe, S., 1988. The Diffusion of Innovations: An Interpretative Survey. In G. Dosi, Freeman, C, Nelson, R., Silverberg, G., Soete, L., eds. *Technical Change and Economic Theory*. London: Pinter Publishers.

OECD, 2011. *Fostering Innovation for Green Growth*, Paris: OECD Green Growth Studies, OECD Publishing.

Oosterhuis, F. ed., 2007. *Innovation dynamics induced by environmental policy*, Amsterdam: Institute for Environmental Studies (IVM). Report commissioned by the European Commission (contract # 07010401/2005/424497/FRA/G1).

Porter, M. & van der Linde, C., 1995. Toward a New Conception of the Environment-Competitiveness Relationship. *Journal of Economic Perspectives*, 9(4), pp.97–118.

Prange, 2008. Explaining Varieties of Regional Innovation Policies in Europe. *European Urban and Regional Studies*, 15(1), pp.39–52.

Quitzow, R., 2011a. Nachhaltigkeitsstrategien: Form und Funktion. In J. Knopf, Quitzow, R., Hoffmann, E., Rotter, M., eds. *Nachhaltigkeitsstrategien in Politik und Wirtschaft*. pp. 123–148.

Quitzow, R., 2013. The Co-evolution of Policy, Market and Industry in the Solar Energy Sector: A Dynamic Analysis of Technological Innovation Systems for Solar Photovoltaics in Germany and China. *FFU Report 01-2013*.

Quitzow, R., 2011b. Towards a Strategic Framework for Promoting Environmental Innovations. *Werkstattbericht Nr. 6 im BMBF-Projekt "Lead Market-Strategien."*

Quitzow, R., 2011c. Towards a strategic framework for promoting environmental innovations. In *Reader for the ETH Academy on Sustainability and Technology 2012*. Zürich: ETH Zürich, Group for Sustainability and Technology.

Quitzow, R., 2012. *Towards a strategic framework for promoting environmental innovations*, Paper presented at the 10th GLOBELICS International Conference in Hangzhou, China, November 9-11, 2012.

Rabe, B.G., 2008. States on Steroids. The Intergovernmental Odyssey of American Climate Policy. *Review of Policy Research*, 28, pp.105–128.

Rabe, B.G., Roman, M. & Dobelis, A., 2006. State competitioin as a source driving climate change mitigation. *NYU Environmental Law Journal*, XIV.

Rayner, J. & Howlett, M., 2009. Introduction : Understanding integrated policy strategies and their evolution. *Policy and Society*, 28, pp.99–109.

REN21, 2011. *Renewables 2011: Global Status Report*, Paris: REN21 Global Secretariat.

REN21, 2012. *Renewables 2012: Global Status Report*, Paris: REN21 Global Secretariat.

REN21, 2013. *Renewables 2013: Global Status Report*, Paris: REN21 Global Secretariat.

REN21, 2014. *Renewables 2014: Global Status Report*, Paris: REN 21 Secretariat.

Del Río González, P., 2008. Policy implications of potential conflicts between short-term and long-term efficiency in CO2 emissions abatement. *Ecological Economics*, 65(2), pp.292–303.

Rogge, K.S. & Reichardt, K., 2013. Towards a more comprehensive policy mix conceptualization for environmental technological change: a literature synthesis. *Working Paper Sustainability and Innovation No. S3/2013 (Fraunhofer ISI)*.

Rosenberg, N., 1972. Factors Affecting the Diffusion of Technology. *Explorations in Economic History*, (Fall).

Rosenberg, N., 1976. *Perspectives on Technology*, Cambridge, UK: Cambridge University Press.

Schmidt, T.S. & Dabur, S., 2013. Explaining the diffusion of biogas in India: a new functional approach considering national borders and technology transfer. *Environmental Economics and Policy Studies*.

Schreurs, M. & Tiberghien, Y., 2007. Multi-Level Reinforcement: Explaining European Union Leadership in Climate Change Mitigation. *Global Environmental Politics*, 7(4), pp.19–46.

SRU, 2002. *Umweltgutachten 2002 des Rates von Sachverständigen für Umweltfragen. Für eine neue Vorreiterrolel*, Berlin: Sachverständigenrat für Umweltfragen, SRU.

Stephenson, P., 2013. Twenty years of multi-level governance: "Where Does It Come From? What Is It? Where Is It Going?." *Journal of European Public Policy*, 20(6), pp.817–837.

Steurer, R., 2007. From Government Strategies to Strategic Public Management: an Exploratory Outlook on the Pursuit of Cross-Sectoral Policy Integration. *European Environment*, 17(3), pp.201–214.

Steurer, R., Martinuzzi, A., 2005. Towards a new pattern of strategy formulation in the public sector: first experiences with national strategies for sustainable development in Europe. *Environment and Planning C: Government and Policy*, 23, pp.455–472.

Tils, R., 2005. *Politische Strategieanalyse. Konzeptionelle Grundlagen und Anwendung in der Umwelt- und Nachhaltigkeitspolitik*, Heidleberg: Springer VS Verlag für Sozialwissenschaften.

Truffer, B. & Coenen, L., 2012. Environmental Innovation and Sustainability Transitions in Regional Studies. *Regional Studies*, 46(1), pp.1–21.

UNEP, 2011. *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication*, Nairobi: United Nations Environment Programme.

Volkery, A., Swanson, D., Jacob, K., Bregha, F., Pintér, L., 2006. Coordination, Challenges, and Innovations in 19 National Sustainable Development Strategies. *World Development*, 34(12), pp.2047–2063.

Watson, J. & Sauter, R., 2011. Sustainable innovation through leapfrogging: a review of the evidence. *International Journal of Technology and Globalisation*, 5, pp.170–189.

WBGU, 2011. *Welt im Wandel: Gesellschaftsvertrag für eine Große Transformation*, Berlin: Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (WBGU).

Wessendorf, F., 2012. *Branchenüberblick PV-Zulieferer*, Frankfurt: Verband Deutscher Maschinen- und Anlagenbau (VDMA).

World Bank, 2012. *Inclusive Green Growth: The Pathway to Sustainable Development*, Washington, DC: World Bank.

World Bank, 2014. *World Development Report 2014: Risk and Opportunity -Managing Risk for Development*, Washington, D.C.: World Bank.

Yeung, H.W. & Coe, N., 2014. Toward a Dynamic Theory of Global Production Networks. *Economic Geography*, in press.

Yin, R., 2008. *Case Study Research: Design and Methods*, London: SAGE Publications.

8. Annex: Papers

Paper #1

The concept of "lead markets" revisited: Contribution to environmental innovation theory

Paper # 1 has been published in *Environmental Innovation and Societal Transitions*, Volume 10, March 2014, Pages 4–19.

The article can be accessed at: http://dx.doi.org/10.1016/j.eist.2013.11.002

Bibliographic reference: Quitzow, R., Walz, R., Köhler, J., Rennings, K. (2014) "The concept of "lead markets" revisited: Contribution to environmental innovation theory", *Environmental Innovation and Societal Transitions*, Volume 10, March 2014, pages 4–19.

Environmental Innovation and Societal Transitions 10 (2014) 4–19

Contents lists available at ScienceDirect

Environmental Innovation and Societal Transitions

journal homepage: www.elsevier.com/locate/eist

The concept of "lead markets" revisited: Contribution to environmental innovation theory

Rainer Quitzow[a,*], Rainer Walz[b,1], Jonathan Köhler[c,2], Klaus Rennings[d,3]

[a] Environmental Policy Research Centre (FFU), Department of Political and Social Sciences, Freie Universität Berlin, Ihnestr. 22, 14195 Berlin, Germany
[b] Competence Center Sustainability and Infrastructure Systems, Fraunhofer Institute for Systems and Innovation Research (ISI), Breslauer Str. 48, 76139 Karlsruhe, Germany
[c] Competence Center Innovation and Technology Management and Foresight, Fraunhofer Institute for Systems and Innovation Research (ISI), Breslauer Str. 48, 76139 Karlsruhe, Germany
[d] Department of Environmental and Resource Economics, Environmental Management, Zentrum für Europäische Wirtschaftsforschung, L7, 1, 68161 Mannheim, Germany

ARTICLE INFO

Article history:
Received 17 December 2012
Received in revised form 1 October 2013
Accepted 17 November 2013

Keywords:
Competitiveness
Emerging economies
Environmental innovation
Geography of innovation
Sustainability transitions

ABSTRACT

The economic potential of lead markets for environmental technologies has served as an important justification for policies to promote environmental innovations in Europe. The emergence of competition from emerging economies has revealed that a domestic lead market is no guarantee for long-term competitive success in an international context. This article reviews the academic literature on lead markets as well as its application in policy. It outlines the theoretical foundations of the concept and main insights obtained with it and relates these to its uses in policy. It then contrasts the lead market approach with the technological innovation systems framework and the multi-level perspective as these are both frequently employed in the transitions literature. The article addresses shortcomings of the current literature and proposes a number of avenues for further development of the concept.

* Corresponding author. Tel.: +49 30 838 56688; fax: +49 30 838 56685.
E-mail address: rainer.quitzow@fu-berlin.de (R. Quitzow).
[1] Tel.: +49 721 6809 236; fax: +49 721 6809 135.
[2] Tel.: +49 721 6809 377; fax: +49 721 6809 330.
[3] Tel.: +49 621 1235 207; fax: +49 621 1235 226.

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http://dx.doi.org/10.1016/j.eist.2013.11.002

Paper #2

Dynamics of a policy-driven market: The co-evolution of technological innovation systems for solar photovoltaics in China and Germany

Paper 2 has been accepted for publication in *Environmental Innovation and Societal Transitions* and is available online.

The article can be accessed at: http://dx.doi.org/10.1016/j.eist.2014.12.002

Bibliographic reference: Quitzow, R. (2015) "Dynamics of a policy-driven market: Theco-evolution of technological innovationsystems for solar photovoltaics in China andGermany", *Environmental Innovation and Societal Transitions*, in press.

G Model
EIST-148: No. of Pages 23
ARTICLE IN PRESS

Environmental Innovation and Societal Transitions xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Environmental Innovation and Societal Transitions

journal homepage: www.elsevier.com/locate/eist

Dynamics of a policy-driven market: The co-evolution of technological innovation systems for solar photovoltaics in China and Germany

Rainer Quitzow

Environmental Policy Research Centre (FFU), Department of Political and Social Sciences, Freie Universität Berlin, Ihnestr. 22, 14195 Berlin, Germany

ARTICLE INFO

Available online xxx

Keywords:
Emerging economies
Geography of innovation
Global diffusion of innovation
Lead markets
Technological innovation systems

ABSTRACT

The rise of Chinese solar energy firms has taken many experts by surprise. German policy makers and researchers alike had suggested that the country's ambitious deployment policies would translate into a competitive advantage for the German solar photovoltaics industry. This paper argues that these expectations rested on an outdated model of the international diffusion of innovation. Building on the technological innovation system (TIS) framework and the related system functions approach, the paper thus proposes a new approach for capturing the global dynamics of innovation and industrial development in emerging technology fields. Focusing on a period of dynamic growth in the field of crystalline-based PV technologies, the paper highlights how a set of dynamic and mutual inter-dependencies between an industrialized country (i.e. Germany) and an emerging economy (i.e. China) have driven the development and diffusion of technology in the field.

1. Introduction

The dynamic development of the solar energy sector over the past decade has been closely linked to Germany's ambitious deployment policies. The German solar feed-in tariff triggered an unprecedented

E-mail address: rainer.quitzow@kiss-potsdam.de

http://dx.doi.org/10.1016/j.eist.2014.12.002
2210-4224/

Paper #3

Towards an integrated approach to promoting environmental innovation and national competitiveness

Paper 3 has been published in *Innovation and Development*, Volume 3, Issue 2, pages 277-296.

The article can be accessed at: http://dx.doi.org/10.1080/2157930X.2013.825070

Bibliographic reference: Quitzow, R. (2013) Towards an integrated approach to promoting environmental innovation and national competitiveness, *Innovation and Development*, Volume 3, Issue 2, pages 277-296.

Innovation and Development
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/riad20

Towards an integrated approach to promoting environmental innovation and national competitiveness

Rainer Quitzow[a]
[a] Environmental Policy Research Centre, Otto-Suhr-Institute of Political Science, Department of Political and Social Sciences, Freie Universität Berlin, Ihnestraße 22, 14195 Berlin, Germany

To cite this article: Rainer Quitzow (2013) Towards an integrated approach to promoting environmental innovation and national competitiveness, Innovation and Development, 3:2, 277-296, DOI: 10.1080/2157930X.2013.825070

To link to this article: http://dx.doi.org/10.1080/2157930X.2013.825070

Paper #4

Assessing policy strategies for the promotion of environmental technologies: A review of India's National Solar Mission

Paper 3 has been published in *Research Policy*, Volume 44, Issue 1, pages 233 – 243.

The article can be accessed at: http://dx.doi.org/10.1016/j.respol.2014.09.003

Bibliographic reference: Quitzow, R. (2015) "Assessing policy strategies for the promotion of environmentaltechnologies: A review of India's National Solar Mission", *Research Policy*, Volume 44, Issue 1, pages 233 – 243.

Research Policy 44 (2015) 233–243

Contents lists available at ScienceDirect

Research Policy

journal homepage: www.elsevier.com/locate/respol

Assessing policy strategies for the promotion of environmental technologies: A review of India's National Solar Mission

Rainer Quitzow*

Environmental Policy Research Centre, Freie Universität Berlin, Ihnestr. 22, 14195 Berlin, Germany

ARTICLE INFO

Article history:
Received 20 December 2012
Received in revised form 4 September 2014
Accepted 8 September 2014
Available online 26 September 2014

Keywords:
Environmental innovation
Technological change
Strategy
Policy mix
Governance
Solar energy

ABSTRACT

There is widespread consensus that no individual policy instrument but rather a "policy mix" is needed to effectively drive the development and diffusion of environmental technologies. However, what exactly constitutes such a policy mix remains largely undefined. This paper takes this discussion a step further by developing a comprehensive framework for assessing and comparing policy approaches for the promotion of environmental technologies. It begins with a critical review of existing policy mix concepts, pointing out key shortcomings. To address the identified challenges, it proposes the concept of a policy strategy as an alternative framework for policy assessment and comparison. This serves as the basis for integrating findings from the literature on environmental innovation and technological change in a comprehensive framework for assessing policy strategies for the promotion of environmental technologies. The framework is then applied for the assessment of India's National Solar Mission, the country's strategy for promoting solar energy technologies. Based on the resulting findings, the potential and limitations of the proposed framework are discussed.