Diss. ETH No. 20035

The Role of Policy in Inducing Technological Change – the Case of Climate Change and the Electricity Sector

A dissertation submitted to

ETH ZURICH

for the degree of

Doctor of Sciences

Presented by

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2011

„Wo aber Gefahr ist, wächst das Rettende auch.“

(But where danger is deliverance also grows.)

Friedrich Hölderlin

Acknowledgements

First I would like to thank daidalosnet.de. In 2005, browsing the job market on daidalosnet.de (during a not so exciting training), I came across ETH Zurich's Chair of Sustainability and Technology (SusTec) and the invitation to apply for master theses. Though I still had two more years to go with my studies of Electrical Engineering in Munich, I memorised the group as it seemed to be doing very interesting research, especially for a person who was very interested in the social and economic aspects of technology. So I applied in 2007 and got accepted. Really liking SusTec's research and having become acquainted with the group during my thesis (and the group having become acquainted with me) Prof. Hoffmann and I decided I should continue as a PhD student. Doing a PhD was something I always strived for. Also after my PhD I will stay with SusTec, this time as a post-doctoral researcher. When relating this course of events to the theories I use in my research, one might either speak of a "sustainable career track" or suspect a certain lock-in of myself. While both might be true, I am very pleased with this situation and look forward to continuing my academic journey on the SusTec "boat" (which is becoming more and more a "ship"). Nevertheless, I will keep scrutinizing the situation and hope I will be able to unlock the lock-in, if I see the need to change the "boat" or choose an entirely different "means of transport". Overall, I am grateful to many people who supported me during the last three and a half years.

First and foremost I want to thank my supervisor, Prof. Dr. Volker Hoffmann, for providing me with the opportunity to write this thesis. Amongst others, three things made him an outstanding person to work for and with: first, his very valuable feedback on many papers and ideas, which certainly improved the quality of this thesis; second, his integrative nature, which helps to avoid conflicts or leads to quick compromise or even consensus; and third, the freedom he provides to the people working for him regarding their research topics as well as their organisation of work.
I also thank Prof. Dr. Marko Hekkert and Prof. Dr. Pablo del Rio, for co-examining this thesis, and Prof. Dr. Thomas Rutherford for taking over the assessor's position during my doctoral examination. Furthermore, I am very grateful to Dr. Malte Schneider, who was an excellent post-doctoral supervisor during my thesis and who became a very good friend. His many ideas, great commitment and precise criticism strongly improved my work and shaped my thinking. Many thanks also go to my further co-authors, Dr. Karoline Rogge, Michael Peters, Jörn Hünteler, Robin Born, Martin "Peitsche" Schuetz, Sandeep Dabur, David Wiederkehr, Dr. Francois Beaurain, Cyrill Rogger and Prof. Dr. Norichika Kanie. Also I thank Grace Gross-Durant for doing all the language checks of my papers. At this point, I would also like to thank again Norichika-sensei and Marko for hosting me in Tokyo and Utrecht (sitting in the best office of the entire floor) for several weeks during my thesis. I had a great time at both places. I am furthermore grateful to Prof. Dr. Masachika Suzuki for initially inviting me to Japan. Special thanks go again to my colleague and friend Michael Peters, who enabled me to learn a lot about "the firm" without having had to work for it. I also thank my former student Simon Sinsel, who

strongly contributed to a working paper, which is not part of this thesis but improved my understanding of innovation systems. Finally, I want to thank all members of the SusTec team and the neighbouring groups who made “living” at the Kreuzplatz office very entertaining.

For financial support, I thank the ‘VolkswagenStiftung‘, the ‘Stiftung zur Förderung der Forschung und Ausbildung in Unternehmenswissenschaften an der ETH Zürich‘ and the ‘ClimPol‘ cluster of the CCES, ETH Zurich. Furthermore, I thank the German National Academic Foundation (Studienstiftung des Deutschen Volkes) for the financial and immaterial support during my studies and the ‘ETH exchange scholarships for excellent young ETH Zurich researchers’ for supporting my stay in Tokyo.

Apart from the people whom I interacted with during my research, I want to thank all my friends. Special thanks go to Rebecca Ashapa for teaching me how to do rock climbing and taking me on many tours, Emrah Kati for taking me to my first Yoga class, Peter Stein for bringing me back to tennis and my best friend Benedikt Baumgartner for many good journeys, talks and parties helping to blow the research cobwebs away. Finally and above all, I want to thank my parents for their constant support during my studies, for giving me a good self-confidence via their education and for helping me in many important decisions.

Abstract

Energy is at the top of the global agenda. Besides other issues, anthropogenic climate change, which is strongly related to energy service provision, poses serious threats to society making deep emission cuts necessary to mitigate climate change. The electricity sector, which is the focus of this dissertation, is particularly interesting: On the one hand, being heavily based on the incineration of fossil fuel it currently contributes most to anthropogenic greenhouse gas emissions. On the other hand, it has high potential for emission reduction. In order reduce CO_2-emissions at the amount and within the timeframes demanded by natural scientists, the largest share of electricity generation must stem from low-carbon technologies by 2050. Low-carbon technological change, i.e., the development and diffusion of such technologies, is therefore the key lever for climate change mitigation. As the endogenous rate and direction of technological change is insufficient to meet the targets, technological change needs to be accelerated and directed towards low-carbon alternatives. To this end, policy has to address technological change. This in turn entails different challenges in different types of countries: (besides unlocking efficiency potentials) high-income countries need to replace emission intensive with low-carbon technologies, industrialising countries need to decouple their growth from emitting greenhouse gases, least-income countries should leapfrog emitting technologies and base the introduction of modern energy services on low-carbon technologies. The Kyoto Protocol of 1997, introducing emission trading and the Clean Development Mechanism, was a first (global) step towards enacting policies aiming at these targets. In addition and (mostly) in order to achieve the Kyoto protocol’s targets, a multitude of policies aiming at the decarbonisation of the power sector and other key sectors for climate change have been enacted in many countries. Of these, the EU’s Emission Trading System (EU ETS), which transferred emissions trading to companies and thereby created the largest carbon market in the world, is most prominent. However, despite these policies global emissions are rising, making the introduction of more effective policy vital. This thesis aims at supporting policy makers in this regard by providing new insights on the question of *how policy can induce technological change towards strong decarbonisation of the electricity sector*.

Two aspects are particularly important for policy makers: first, the necessary height and form of incentives in various countries for different technologies which perform differently not only with regards to their cost or emissions balances but also to their contributions to sustainable development; second, the effects of currently installed policies on the actors relevant for innovation and their innovation decisions which can unveil the potential for improvement in the policy mix. To analyse both aspects, six studies were performed based on differing (mainly quantitative) methodologies and positioned at two different theoretical and analytical levels, a macro- and a micro-level. For the first aspect, four papers on the macro-level compare countries and/or technologies based on three methods: techno-economic modelling, a comparative case study of two countries as well as multi-criteria assessment. Of the four papers, two analyse developing countries, one study focuses on developed countries and one considers both groups of countries. For the second aspect, two papers on the micro-, i.e., actor-level, analyse the effects of the current policy mix on relevant actors' R&D and diffusion decisions. Both are based on statistical analyses of original data stemming from a survey conducted amongst power generators and power generation technology providers in seven EU countries.

This dissertation makes three main contributions. First, a contribution lies in combining analyses from two different levels of analyses and theory and the application of different methods appropriate for analysing the various sub-aspects of the research question. Second, a theoretical contribution is made by combining cognitive organisational theory with evolutionary innovation studies and thereby making the implicit element of cognition explicit in evolutionary economic theory. Third, the empirical data generated represent a contribution as it provides new insights on the cost, emission reduction potential and further performance dimensions of various technologies and the effects of currently installed climate-relevant policies. This empirical contribution provides a better understanding of the necessary policy support for certain technologies in different contexts over time and the role of different instruments for this purpose.

The findings of the individual papers allow us to derive corresponding policy recommendations. In order to support low-carbon technologies effectively and efficiently policy needs to differentiate technologies and countries concurrently as specific country-technology combinations vary strongly regarding their incremental costs. Furthermore, in order to increase policy efficiency and avoid wrong incentives, the support should be dynamic and correspond to technological learning and cost reductions. Regarding the instruments, our study concurs with authors calling for a policy mix. One (market-based) instrument is not enough to correct for market failures other than the emission externality, unless the price for the emission certificate is assumed at an unrealistic height. However, our results also support the belief that the policy mixes currently in place need to become more effective. In the EU, there is potential for improvement of the EU ETS (e.g., by introducing an "innovation accelerator" in the allocation schemes) as well as the other policies complementing it. In developing countries, the Nationally Appropriate Mitigation Activities (NAMAs), policies that are formulated on country level and supported internationally, currently being discussed are more suited for fostering the diffusion of low-carbon technologies than a reformed Clean Development Mechanism, according to our findings. NAMAs can integrate several measures into a consistent policy mix, and thus – amongst other impacts – address the removal of fuel subsidies. As our findings empirically confirm the negative effect of adverse incentives set by the rules for emission rights allocations, countries planning to introduce emissions trading should avoid the mistakes made during the first phases of the EU ETS. Overall, the thesis arrives at the conclusion that shifting the policy focus away from mere treatment of climate change towards energy policy with an integrated objective of climate protection might be an effective way forward. To this end, the thesis concludes with proposals for future research.

Zusammenfassung

Das Thema Energie steht weit oben auf der globalen Agenda. Neben anderen Problemen, stellt anthropogener Klimawandel, der stark mit der Bereitstellung von Energie-basierten Serviceleistungen zusammenhängt, eine erste Gefahr für die Menschheit dar. Der Stromsektor, der im Zentrum dieser Dissertation steht, ist hierbei von besonderem Interesse: Einerseits ist dieser Sektor derjenige, der aufgrund seiner grossen Abhängigkeit von fossilen Rohstoffen (also Kohlenstoffen), am stärksten zu anthropogenen Treibhausgasemissionen beiträgt, andererseits hat er hohes Potential für eine kohlenstoffarme Zukunft. Um CO_2- Emissionsreduktionen in einem Umfang und innerhalb eines Zeitraums wie von Naturwissenschaftlern gefordert zu erzielen, muss der Grossteil der Stromerzeugung bis 2050 auf emissionsarme Technologien umgestellt werden. Emissionsreduzierender technologischer Wandel ist daher der wichtigste Hebel zur Minderung des Klimawandels. Nachdem die endogene Geschwindigkeit und Richtung von technologischem Wandel nicht ausreicht, um dieses Ziel zu erreichen, muss technologischer Wandel beschleunigt und in Richtung emissionsarme Technologien umgelenkt werden. Hierfür muss Politik eingreifen, was verschiedene Herausforderungen in unterschiedlichen Ländern beinhaltet: Während entwickelte Länder (neben dem Heben von Effizienzpotentialen) ihre Stromerzeugung auf emissionsarme Technologien umstellen müssen, sollten Schwellenländer ihr Wachstum vom Emissionsanstieg entkoppeln. Entwicklungsländer sollten die Chance nutzen, kohlenstoffbasierte Stromerzeugung zu überspringen und die Einführung moderner Energiebereitstellung direkt auf emissionsarme Technologien basieren. Das Kyoto Protokoll von 1997 war ein erster (globaler) Schritt zur Erreichung dieser Ziele, indem es Emissionshandel und den Clean Development Mechanism, ein Mechanismus durch den sich entwickelte Länder Emissionsreduktionen durch Projekte in Entwicklungsländern anerkennen lassen können, eingeführt hat. Zusätzlich, und (meist) um die Ziele des Kyoto Protokolls zu erreichen, haben viele Länder eine Reihe an politischen Massnahmen getroffen, die auf einen kohlenstoffarmen Stromsektor zielen. Das Emissionshandelssystem der EU (EU ETS), was einen Emissionshandel für Unternehmen einführte und dadurch den weltgrössten CO_2-Zertifikate Markt schuf, is das prominenteste Politikinstrument. Trotz dieser Massnahmen, sind die globalen Treibhausgas Emissionen gestiegen, was eine effektivere Politik unabkömmlich macht. Diese Dissertation hat daher das Ziel, politische Entscheidungsträger zu unterstützen, indem sie neue Einsichten auf die folgende Frage liefert: *Wie kann Politik technologischen Wandel hin zu einer starken Entkarbonisierung des Stromsektors induzieren?*

Zwei Aspekte sind dabei für Politiker besonders wichtig: erstens, die Höhe und Form der Anreize, die notwendig ist, um in verschiedenen Ländern unterschiedliche emissionsarme Technologien zu unterstützen, zumal diese unterschiedliche Leistungen erbringen hinsichtlich ihrer Kosten, ihrer Emissionsbilanz und ihres potentiellen Beitrags zu nachhaltiger Entwicklung; zweitens, die Effekte des aktuellen Politikmix auf innovationsrelevante Akteure – also Firmen – und ihre

Innovationsentscheidungen, welche Rückschlüsse auf Verbesserungspotential des Politikmix zulassen. Um beide Aspekte zu untersuchen, wurden sechs Studien ausgearbeitet, die auf unterschiedlichen (meist quantitativen) Methoden beruhen und zwei Analyse- und Theorieebenen umfassen: eine *Mikro-* und eine *Makro-Ebene*. Hinsichtlich des ersten Aspekts werden in vier Studien auf der Makro-Ebene Technologien und/oder Länder basiert auf tech no-ökonomisch Modellierung, einer vergleichenden Länderfallstudie, sowie einer Multikriterien-Analyse verglichen. Von diesen vier Studien analysieren zwei ausschliesslich Entwicklungsländer, eine fokussiert auf entwickelte Lände, eine weitere behandelt beide Gruppen von Ländern. Bezüglich des zweiten Aspekts analysieren zwei Studien auf der Mikro-, also Akteurs-Ebene, die Effekte des aktuellen Politikmix auf die F&E- und Diffusionsentscheidungen relevanter Akteure. Beide Studien basieren auf statistischen Analysen von originären Daten, die aus einer Umfrage unter Stromerzeugern und Stromerzeugungs-Technologieherstellern in sieben EU Ländern stammen.

Diese Dissertation liefert drei Hauptbeiträge. Der erste Beitrag liegt in der Kombination zweier Analyse- und Theorieebenen sowie der Verwendung verschiedener Methoden, die je nach Unteraspekt der zu untersuchenden Forschungsfrage gewählt sind. Der zweite Beitrag wird durch die Kombination von organisationaler kognitiver Theorie mit evolutionären Innovationsstudien gemacht und der damit einhergehenden expliziten Berücksichtigung des implizit in evolutionsökonomischer Theorie enthaltenen Elements *Kognition*. Der dritte Beitrag gründet auf der Generierung neuer Datenpunkte, die neue Einsichten in die Kosten, das Emissionsreduktionspotential und weitere Leitungsmerkmale von Technologien, sowie die Effekte derzeit gültiger klimarelevanter Regulierung. Dieser empirische Beitrag ermöglicht ein besseres Verständnis der notwendigen politischen Unterstützung für verschiedene Technologien in unterschiedlichen Kontexten und über Zeit, sowie die Rolle verschiedener Politikinstrumente die diesem Zweck dienen.

Die Ergebnisse unserer Studien erlauben, entsprechende Politikempfehlungen abzuleiten. Um emissionsarme Technologien effektiv und effizient zu fördern, muss Politik gleichzeitig nach Technologien und Ländern differenzieren, da jede spezifische Länder-Technologie Kombination sehr unterschiedliche inkrementelle Kosten aufweisen kann. Darüber hinaus sollte, um die Effizienz der Politik zu erhöhen und keine falschen Anreize zu setzen, die Förderung dynamisch sein. Damit kann sie dem technologischen Fortschritt und den damit einhergehenden Kostenreduktionen gerecht werden. Bezüglich der politischen Instrumente bestätigt diese Dissertation diejenigen Autoren, die einen Instrumentenmix befürworten. Ein einzelnes (marktbasiertes) Instrument ist nicht ausreichend, um andere Marktversagen als die Verschmutzung des Gemeingutes Atmosphäre auszugleichen, wenn der Preis für Emissionszertifikate bei einer realistischen Höhe angenommen wird. Die Ergebnisse der Dissertation legen allerdings auch nahe, dass die aktuelle Politik effektiver werden muss. Innerhalb der EU besteht das Verbesserungspotential für den EU ETS (zum Beispiel durch die Einführung eines „Innovationsbeschleunigers“ für die Zuteilung der freien Emissionszertifikate) sowie weitere

Instrumente, die das ETS komplementieren. In Entwicklungsländern zeigen die Ergebnisse der Dissertation, dass „Nationally Appropriate Mitigation Actions (NAMAs)“, politische Instrumente, die national eingeführt aber international unterstützt werden, besser für die Förderung der Diffusion von emissionsarmen Technologien geeignet sind als ein reformierter Clean Development Mechanism. NAMAs können verschiedene Instrumente in einem konsistenten Politikmix kombinieren und dadurch, neben anderen Dingen, auch die Abschaffung von Subventionen für fossile Brennstoffe umfassen. Unsere Ergebnisse zeigen empirisch den kritischen Effekt der ungünstigen Anreize, die durch die Zuteilungsregeln für Emissionszertifikate in den frühen Phasen gesetzt wurden. Daher sollten Länder, die planen ebenfalls einen Emissionshandel einzuführen, diese Fehler vermeiden. Im Ganzen kommt diese Dissertation zu dem Schluss, dass eine Verschiebung des politischen Fokus weg von reinem Klimaschutz, hin zu Energiepolitik mit dem integrierten Ziel Klimaschutz ein effektiver Ansatz für die Zukunft ist. Zu diesem Zweck werden Vorschläge für zukünftige Forschungsaktivitäten erarbeitet.

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1. Introduction

The use of modern technology is interlinked with the industrial era and has resulted in significant societal advancement. However, it also causes severe problems. Anthropogenic climate change is one (of several) pressing issues which arise from the use of modern technology (UNFCCC, 1992). As climate change is by large related to energy technologies and energy related services are at the heart of our economy, it poses serious threats to mankind. However, technical solutions, such as renewable energy technologies (RET), can be developed and deployed (and complemented by other measures), which address the issue of climate change. This however is not a trivial task. This thesis is a socio-economic analysis on technology and its interaction with society and nature. Its main aim is to provide feedback for policy makers on how to induce a transition towards an economy that is based on the provision of low-carbon services.

Technological change as key lever to address climate change

After several decades of climate research, global warming is now recognised as fact not only by researchers but also by most countries' leaders and the majority of many countries' populations. In order to limit global warming to 2°C, which as seen as an important threshold to avoid non-reversible damage to the nature and mankind (Stern, 2006; UNFCCC, 2011), the amount of CO_2 in the atmosphere has to be limited to 350 to 450ppm by 2050 (IPCC, 2007b, c; Knutti and Hegerl, 2008). To this end, massive greenhouse gas (GHG) emission reductions are necessary, imposing a substantial deviation from business as usual (BAU). The large majority of GHG emissions is related to the provision of energy services (IPCC, 2007a), the demand for which is set to rise with expected economic growth (Tainter, 2011). Hence, energy related sectors, such as transport, mining and refining, industry, heating and electricity generation, need to deliver most of the reductions (IEA, 2010b). Electricity generation is the sector contributing most to anthropogenic GHG emissions but has high decarbonisation potential: It is expected that of the 21 billion tonnes CO_{2e} emission abatements that are needed by 2035 to achieve the 450ppm target, over 40% can be delivered by the power sector. (IEA, 2010b) The scope of this thesis is therefore on the electricity sector.

Today the global electricity generation mix is made up of fossil sources (mainly coal and gas) followed by hydro, nuclear, wind and other renewables (IEA, 2010b; Nakicenovic and Nordhaus, 2011). This mix results in a specific GHG intensity of $536gCO_2/kWh$ (IEA, 2010b). In order to reduce this value to the degree and within the timeframe set by natural scientists (for 2035, the IEA suggests a target which is at a quarter of today's value), technological change must strongly accelerate and drastically redirect towards low-carbon solutions (which should be accompanied by a behavioural change among electricity end users). This however poses different challenges in different contexts: While for high-income countries decarbonising the electricity sector means that efficiency potentials need to be unlocked and existing fossil fuel based infrastructure needs to be replaced with low-emission technologies, middle-income countries have to decouple their growth from energy consumption. Low-income countries, where modern energy technologies are often not yet installed, should leapfrog the fossil era of power generation and directly base modern energy service provision on low-carbon solutions (UN-AGECC, 2010). To address these challenges in a cost efficient manner it is essential to understand how technological change can be accelerated and redirected accordingly. Technological change comprises the three interacting stages of technology invention, innovation and diffusion (Schumpeter, 1942). “The cumulative economic or environmental impact of new technology results from all three of these stages” (Jaffe et al., 2002, p. 43). However, while technology is at the core of our economy, “technological change is at once the most important and least understood feature driving the future cost of climate change mitigation” (Pizer and Popp, 2008). In order to better understand how technological change progresses, recalling history might be insightful.

What can we learn from historical technological change?

In the power sector, we have seen dramatic technological change over the centuries which throughout its course showed an increase in efficiency and a reduction of power production cost. While at the beginning of human development mankind could only use their own manpower, this changed with the domestication of animals. Oxen and horses provided additional power with an increase in horse power during the first half of the second millennium AD due to technological improvements in horse management, e.g., new harness techniques, leading to higher efficiency per animal (Langdon, 1986).

Besides animal power windmills and waterwheels provided power, this was at low level however. While improvements in both technologies strongly raised their efficiency, another technology became dominant, not because of its lower power production cost but rather because of its reliability compared to intermittent windmills and waterwheels: the steam engine. By 1850, steam power had become the prime source of power in Britain (Fouquet, 2008). This means that even in the then most industrialised society of the world fossil, non-renewable sources of power overtook renewable sources only 160 years ago. CO_2-emissions for power generation rose with the diffusion of this technology.

However, the steam engine was also slowly replaced. Though electric power was more expensive than steam power in the beginning, it had the big advantage of flexibility and transportability, i.e., one did not have to own a power generation device to use its power. Therefore small consumers for which a steam engine would have been too large and/or expensive could also use non-manpowered devices (Devine, 1983; Fouquet, 2008). Due to strong efficiency gains and economies of scale based on unified standards in the early 20th century, the cost of electric power generation fell below those of steam power, virtually eliminating the latter (Fouquet, 2008). While electricity has remained by far the most important source of power in most sectors (leading to the almost identical meaning of power sector and electricity sector), within electricity generation we have also seen strong technological change. In the 19th century electricity was generated exclusively from coal and hydro power. Other sources (oil, gas, biomass, nuclear, wind, solar) gained market shares in the 20th century, finally arriving at the aforementioned generation mix of today. Within all technologies, constant efficiency increases and generation cost reductions are observable.

The lesson from this historical excursus is that (a) technological change is an ever ongoing historic process (Dosi, 1988b) in which (b) various techniques compete in markets and actors select amongst these alternatives (Nelson and Winter, 1982) (c) based on prices and other dimensions of merit (Anderson and Tushman, 1990). However, two further things become clear: First, the endogenous rate of technological change is too slow to address the urgency of the climate challenge (compare the aforementioned need for significant decarbonisation by 2050). Second, technological change is not directed. As long as emissions are irrelevant for the decision making of actors, the emission intensity of a technology will not be an important criterion for technological change. This is where policy comes into play. Policy needs to deliver incentives that make the common good of the atmosphere (Ostrom, 1990) a relevant determinant of technological change, by putting a price on GHG emissions for instance[1]. Hence, the focus of this thesis is the role of policy for technological change in the power sector.

The mutual interaction of policy and technological change

In this dissertation, we follow the strand of authors that regard "policy making (...) as a continuing process" which interacts with technological change (Nelson, 2009, p. 11). Figure 1 depicts this interaction as seen in this thesis. As society is based on nature and its resources and policy's major task is to preserve society's well-being in the long-term, policy needs to also protect nature. In case technological change brings about societal or environmental problems (often articulated by activist groups) policy can react and address these problems by inducing alterations in the rate and direction of technological change. While society and nature can also have direct effects on technological change, this dissertation is focused on the (potential) effects of policy on technological change (indicated by the bold arrow in Figure 1).

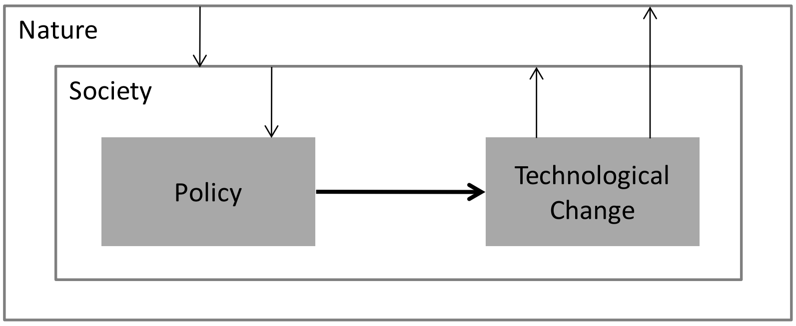

Figure 1: The interaction of policy and technological change

A brief summary of the history of power sector regulation serves as good example underpinning this view on the interaction of policy and technological change: While nowadays one of the most regulated economic sectors, historically the power sector was rather unregulated. However, the provision of coal-based energy services resulted in many mining accidents which increased societal pressure on

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[1] Voluntary approaches, e.g., by final customers who are willing to pay more for a climate friendly service or firms reducing emissions voluntarily, can support this effect, but are not able to bring about the drastic change necessary. (Dietz et al., 2003; Rabe, 2004)

policy makers and thereby led to political regulation. Safety standards were introduced, leading to (incremental) technological change in mining. The regulation of SO_x emissions to reduce the related forest decline represents an example of policy inducing technological change (in this case the diffusion of electrostatic precipitators) to address environmental issues, which were articulated by societal actors, i.e., environmental activist groups[2]. (Fouquet, 2008) Climate change stemming from technological change in the power sector is certainly a major threat to nature and society and is therefore addressed by climate and complementary policy, which in turns aims at low-carbon technological change.

Climate policy and complementary policy elements

While it took several decades to recognise the environmental and societal issue of climate change (e.g., Oreskes, 2004; Trumbo, 1996), policy has begun to act. During the 1992 UN summit in Rio, the United Nations Framework Convention on Climate Change (UNFCCC) was founded with the aim of counteracting climate change on a global level (UNFCCC, 1992). Five years later, the first global agreement under this convention was signed, the Kyoto Protocol (KP). It differentiates between industrialised and non-industrialised countries and imposes emission reduction obligations on the former (aiming at a 5.2% reduction on average by the period of 2008-12 compared to 1990 levels) while leaving the latter without obligations. However, the latter are also addressed by the KP: the project-based Clean Development Mechanism (CDM) allows industrialised countries to partly realise their emission reduction obligations in non-industrialised countries. Developed countries are equipped with the possibility of emissions trading (UNFCCC, 1997).

While the KP works on a country-level, the European Union decided to realize these emission reduction targets by installing an Emissions Trading System (EU ETS) on the corporate level. Companies from emission intensive sectors are required to own pollution rights in order to emit, which they can trade on markets. The electricity sector is particularly targeted by this system, not only because of its high contributions to GHG emissions but also because “leakage” due to industry relocations to non-regulated countries is impossible (unlike for commodities such as steel). The CDM is coupled to the EU ETS, so that firm regulated by the EU ETS can partly offset their emissions through CDM projects in developing countries. In essence, what these market-based climate policy instruments do is put a price on GHG emissions. This form of penalising emissions represents a technology-neutral demand-pull instrument (Azar and Sandén, 2011) as it increases the economic competitiveness of low-carbon technologies over emission intensive technologies, thereby pulling them into the market, based purely on emissions. However, if the carbon price is not extraordinarily high, technologies that are currently further away from competitiveness – but might have a large cost

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[2] Another intriguing example is the introduction of nuclear power plants in Sweden where in the 1950s and 60s green activists lobbied for regulation to promote nuclear power in order to protect rivers from new hydro power plants (Kaijser, 1992).

and GHG reduction potential – might not profit from the carbon price[3]. Furthermore, the historical summary above showed that costs are one but not the only merit dimension of users and that technological change is determined by other factors, which may not be addressed by putting a price on carbon.

Hence, an academic debate on how to induce such decarbonisation through policy revolves around the question of whether one climate policy instrument, such as emissions trading, is preferable or whether a mix of policy elements is needed (Fischer and Preonas, 2010; Philibert, 2011). Authors preferring a single instrument predominantly favour emissions trading over other options and argue that additional policy instruments undermine the efficiency of climate policy due to interaction effects[4] (e.g., Böhringer and Rosendahl, 2009). Other authors argue that further, mainly technology-specific instruments, which complement emissions trading in a consistent policy mix that supports the emission reduction targets, are required to induce technological change at the pace and in the direction needed in order to prevent dangerous global warming (del Río González, 2008; Jacobsson and Bergek, 2004; Jänicke and Lindemann, 2010; Kern and Howlett, 2009; Rogge et al., 2011b; Sijm, 2005; Sorrell and Sijm, 2003). In their eyes, emissions trading alone cannot address other barriers than the emission externality which stand in the way of the low carbon transition. Technology-specific instruments complementing a carbon price mechanism can act as demand-pull (e.g., in the form of preferential feed-in tariffs for renewables) or technology-push policies (e.g., in form of R&D subsidies for renewables).

Room for improvement in policy and underpinning research

Aside from this debate, the political reality in most countries is constituted by a policy mix aiming at low-carbon technological change and not a single instrument such as emissions trading (IEA, 2010a). However, these policy mixes differ strongly regarding their designs (Frondel et al., 2008a), consistency and congruence (Kern and Howlett, 2009), and therefore also their effectiveness. As a consequence GHG emissions have been rising in recent years (ESRL, 2010), which calls for more effective policy as well as for research supporting policy makers. We are standing at the crossroads. With the Kyoto Protocol running out at the end of 2012, a new global climate policy framework needs to be agreed upon. While the Copenhagen Accord and the Cancun Agreement represent some progress in this direction, many questions regarding the future policy mechanisms remain unresolved. In Europe, where most rules for the EU ETS post 2012 are settled until 2020, some details are still open to debate. The discussed rise of the GHG emission reduction target from 20 to 30% by 2020 (The Guardian, 2010) would need to result in a more stringent policy design. However, "research [...] on the incentives that will [...] need to drive the transition to a low-carbon economy is at its infancy" despite

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[3] While authors argue that the introduction of such a price signal will also lead to investments in R&D for technologies further away from competitiveness (Sinn, 2008), production-based cost reductions and learning by using cannot be harnessed.

[4] An example is the combination of a subsidy granted to RET and an ETS. By leading to the diffusion of RET, overall emissions are reduced, leading to a lower certificate price. Thereby, the ETS is undermined.

being “critical to understand and develop the policy instruments that will guide markets, entrepreneurs and not-for profit participants in undertaking the research, development and commercialisation of new technologies” that make this transition possible (Nakicenovic and Nordhaus, 2011, p. 565).

Aim and structure of the dissertation

This dissertation aims to address this research gap and thereby support policy makers. It provides recommendations on how to design and adjust policy mixes that incentivise the decarbonisation of the power sector and thereby make them more effective. The following section lays out the overall objective of the thesis and its embedding into theory (Section 2). The methods and data used are explained in Section 3, while each paper and its findings are summarised in Section 4. The dissertation concludes by describing its contributions and proposing policy recommendations (Section 5). Section 6 gives an overview of all papers, the full versions of which can be found in Annex 1.

2. Objectives and Theoretical Background

The need for climate-relevant policies to become more effective on a global scale was described in Section 1. To support policy makers in this regard, the main objective of this thesis is to provide new insights on the question *how* ***policy*** *can induce* ***technological change*** *towards strong* ***decarbonisation of the electricity sector***.

While there is great consensus that low-carbon technological change depends on policy incentives, the degree of these incentives and the appropriate instruments that provide them on international and national level remain heavily discussed (see e.g., Bakker et al., 2011; Fischer and Newell, 2008; Fischer and Preonas, 2010; Hoehne, 2011; Neuhoff, 2011b). Two sub-questions can be derived from these debates: First, *how do different alternative low-carbon technologies compare regarding their cost and other important merit dimensions in different contexts?* Second, *how do currently installed climate-relevant policies induce technological change by incentivising alterations in the R&D and diffusion activities of relevant firms in the sector?* Results on the first question can deliver insights on the type (i.e., a single instrument or a mix) and height of policy incentive needed to support these technologies. Results on the second question can provide insights into the (potential) role of different policy instruments and their design for technological change and thereby unveil potential for improvements of the existing policy.

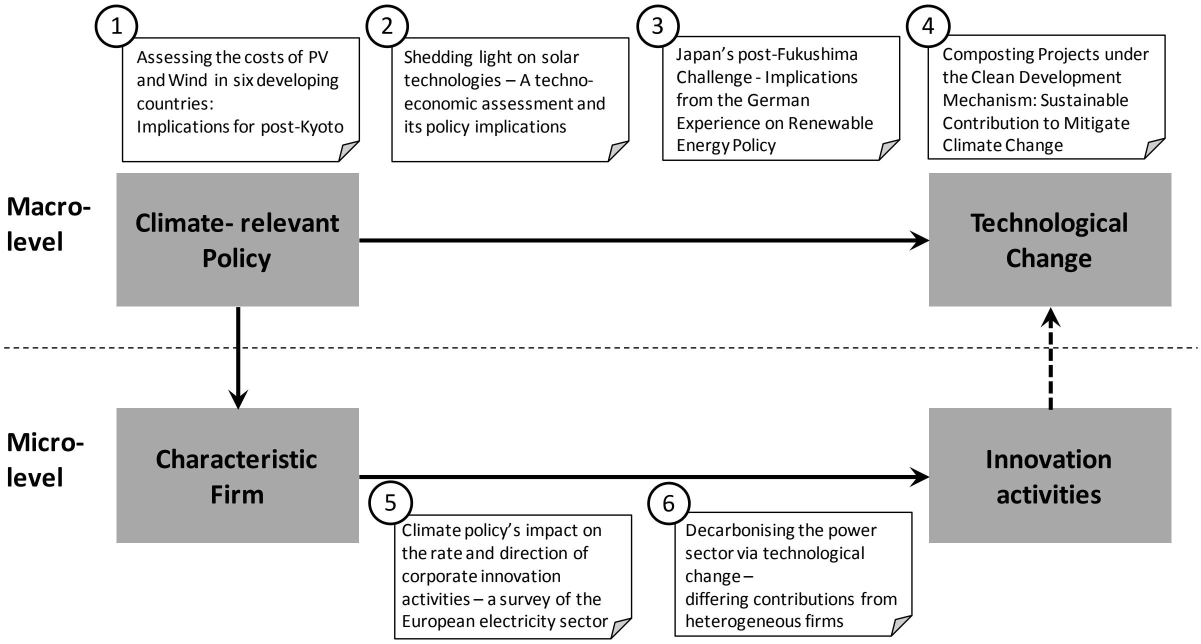

Figure 2: The overall dissertation framework. The white boxes show the title and number of each of the dissertation's papers.

The dissertations framework is depicted in Figure 2. The two sub-questions are analysed at two different analytical levels: a macro and a micro level. The papers on the macro-level mainly target the first- sub-question and provide direct policy recommendations from comparing technologies and/or countries. The papers on the micro level target the second sub-question and assume that various policy elements affect firms with heterogeneous attributes differently and lead to heterogeneous changes in their innovation activities. As indicated in Figure 2, both levels interact in two ways: (i) policy trickles down to individual firms, which change their innovation activities and (ii) thereby alter the course of technological change on the macro (i.e., sector) level. By analysing the (potential) role of policy in technological change on both levels – micro and macro – we follow Kemp and Pontoglio's (2008) proposal to look at the innovation effects of policy from different standpoints.

This thesis applies a broad view regarding the national scope because different countries face different challenges when attempting to decarbonise the power sector (see Section 1). More specifically, this thesis distinguishes between developing and developed (mainly EU) countries. The former are considered in order to provide insights on potential (global) post-Kyoto regulation. The latter are taken into account in order to provide feedback for potential improvements of the policy mixes installed in these countries and provide lessons learned to other countries planning to introduce similar policies.

The macro-level

The first four papers of this dissertation operate at the macro level. They are not strongly founded in economic theory but implicitly assume that technologies with better performance characteristics will prevail if incentivised accordingly. As most low-carbon technologies are not yet competitive with established fossil fuel-based technologies, it is important to understand how much policy support they need in order to unlock their cost reduction potential. This is reflected in a growing body of literature analysing the performance characteristics and diffusion patterns of low-carbon technologies. Yet the highly diverse - and continuously changing - economic and political landscape in the energy sector implies a persistent need for further, fine-grained assessments.

Of the four papers on the *macro level*, two – Papers 1 and 2 – assess the current and future cost of selected renewable energy technologies (solar and wind) and aim at deducing the magnitude of policy support needed in order to bring these technologies close to competitiveness. To obtain a more differentiated picture regarding the required support, the papers address three important determinants of technological competitiveness: technology difference, country differences and time. By analysing different technologies in different contexts over time, a fine-grained picture on the necessary type and height of incentive for the diffusion low-carbon technologies can be drawn.

Country differences and similarities are also the topic of Paper 3. We analyse the new situation of the Japanese electricity sector after the Fukushima accident and calculate the resulting demand for new technologies. Building thereon, parallels to Germany are drawn, where the transition of the power sector was accelerated and redirected strongly by policy incentives in the past ten years. Despite the large differences between the countries, we argue that the German experience may proof valuable for Japanese energy politics, regarding both success factors and potential pitfalls.

However, a pure focus on the cost and GHG reduction potential of low-carbon technologies bears the risk of overlooking other important properties of technologies. Other important technology performance criteria relevant for sustainability need to be analysed, which is done in Paper 4. Fukushima is just one example highlighting that too narrow a focus on the climate challenge might entail other environmental and societal risks. The Clean Development Mechanism (CDM) aims at a contribution of its projects to sustainable development. We compare projects in- and outside the electricity sector regarding their potential sustainability contribution and thereby aim at opening eyes for aspects outside the pure climate and electricity focus. The findings of all four papers on the macro level are translated into policy recommendations.

The micro-level

The historic excursus in Section 1 showed that technological change is a complex process in which actors play an important role. This points to the relevance of scrutinizing dynamics on the micro level, since the decisions whether to put efforts into R&D and production and/or adopt new technologies are made by a population of heterogeneous firms. These firms make their decisions not only based on the technologies' (prospective) costs, but also on other motives, such as their extant technology portfolio, their capabilities, and their resources. Therefore, evolutionary innovation scholars argue that it is important to consider the actors responsible for the invention, innovation and diffusion of technology - and thereby open the "black box" of innovation (Dosi, 1997; Faber and Frenken, 2009; Rosenberg, 1982; van den Bergh, 2007). We follow this suggestion and add a micro level to our framework. Evolutionary economic approaches are based on Charles Darwin's principles of evolution – replication, variation, and selection– as well as Schumpeter's (1912, 1942) rejection of equilibriums and vision of technological change as a non-linear process embedded in history and institutions. In this process, "collective interactions within and outside of markets perform as selection mechanisms" (Dosi, 1997, p. 1531). Evolutionary approaches are micro-founded, stressing the role of heterogeneous, boundedly rational actors and their routines as well as the tacitness of the knowledge underlying technological innovation (Dosi, 1988a; Nelson and Winter, 1982).

Due to its strong micro-focus, evolutionary economic theory is not only considered an economic but also an organisational theory (Mintzberg et al., 1998). Therefore, in order to open the second "black box" – the internal strategy making of firms[5] – further organisational theories can be merged with evolutionary economics (Barney, 2001). One important aspect of corporate strategy finding is the firm-specific perception of the environment. Organisational cognitive theory (Dutton and Jackson, 1987; Weick, 1979) aims at understanding the differences in how firms make sense of their business environment, which makes it suitable to analyze heterogeneous responses to changes therein – stemming, e.g., from the introduction of policy Therefore, in the two studies on the micro level (Papers 5 and 6), evolutionary approaches are combined with cognitive approaches from organisational theory.

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[5] Besides other important actors, e.g. universities, firms are the most relevant actors for technological change (Nelson and Winter, 1982; Nelson, 2009), which also accounts for the power sector.

Both papers try to understand the role of policy as a change in the business environment of actors relevant for technological change in the electricity sector. Their reactions in form of changes of their R&D and diffusion activities can vary strongly. Paper 5 aims to explain the role of the different elements in the current policy mix on technological change by analysing the perception of these elements and innovative reaction by producers and users of technology in the power sector from seven EU countries. Paper 6 goes in a similar direction by analysing the role of firm heterogeneity for policy-induced technological change. Both papers consider the following policy elements: the EU ETS, long-term emission reduction targets and technology-specific demand pull and push policies. While Paper 5 looks at corporate R&D and adoption activities separately, Paper 6 analyses the integral behaviour of firms, i.e., their decisions to devote resources to R&D and diffusion activities simultaneously. Changes in the actors' innovation decisions are likely to affect the acceleration and redirection of technological change at the macro level, as these activity changes at the micro-level represent the evolutionary mechanisms that can change the structure of a sector in the longer term. This evolving mechanism is however not explicit content of this thesis (compare the dashed arrow in Figure 2).

Table 1 summarises the six papers and their objectives. While they are positioned at different levels and address different aspects of the research question, all papers aim to provide insights on the role of policy for technological change, and deduce policy recommendations from those insights. To this end, the studies on the macro-level contribute to the understanding of technologies, their performance, cost, characteristics and potentials. This in turn was highly beneficial for understanding and interpretation of the results obtained on the micro-level.

Table 1: Overview over the papers and their research questions

		Title	Research Question(s)
Macro-level	1	Assessing the cost of PV and wind in six developing countries: Implications for post-Kyoto	1) How to determine different countries' financial needs for emission abatement? 2) Which instruments are most effective for distributing financial resources in a post-Kyoto regime?
	2	Shedding light on solar technologies – a techno-economic assessment and its policy implications	What is the competitiveness of leading solar technologies depending on time and location?
	3	Japan's post-Fukushima Challenge - Implications from the German Experience on Renewable Energy Policy	What can Japan learn from German renewable energy technology policy post Fukushima?
	4	Composting projects under the CDM: Sustainable contribution to mitigate climate change	How do composting CDM projects compare to other CDM projects regarding (a) project numbers and (b) their contributions to sustainable development?
Micro-level	5	Climate policy's impact on the rate and direction of corporate innovation activities – a survey of the European electricity sector	What is the impact of climate policy on the rate and direction of corporate innovation activities?
	6	Decarbonising the power sector via technological change – differing contributions from heterogeneous firms	How do firms with diverse characteristics differ regarding their contributions to low-carbon technological change in the power sector?

Analysing macro-effects by 'descending' to the micro-level is a concept well known in sociology. "Explanations that refer to the effects of social structures must be accompanied with a schematic account of the mechanisms through which they bring about the putative effects at the level of locally-situated individual behaviour" (Little, 2007, p. 367). In fact, the framework used in this dissertation shows strong parallels to Esser's (1996, 1999) "*Model of Sociological Explanation*", which deals with the role that changes in "social situations" play for individual actors, how they evaluate that situation based on their preferences and interests and therefore change their behaviour which aggregates via social formation resulting in new social shapes[6].

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[6] In sociology, "orthodox Marxists, for example, would draw their conclusions directly from the macro-level (...) without taking into account the subjective perceptions and actual "consciousness" (...) at the micro-level and the problems of their aggregation" (Trent, 2008) .

3. Methods and Data

The question on the role of policy for low carbon technological change in the power sector is certainly a complex one. Besides the complicatedness of the technologies, the non-linearity of technological change, the country differences and the associated challenges, as well as the diversity of policy instruments and designs add to this complexity. As shown in Section 2, this dissertation tries to handle this complexity by answering different sub-aspects of the question at different theoretical and analytical levels. This in turn necessitates the application of various methods. Several authors (e.g., Little, 1999; Norgaard, 1989) argue that a methodological pluralism is most appropriate when dealing with complex questions in economics and social sciences. This thesis is mainly based on quantitative methods, and relies partly on primary and partly on secondary data (compare Table 2).

Table 2: Methods and data used in the individual papers

	Title	Method	Analysis	Data source	Regional scope	Technological scope
1	Assessing the cost of PV and wind in six developing countries: Implications for post-Kyoto	Techno-economic modelling	Quantitative	Secondary data (technology data)	Developing countries	PV and Wind (and several baseline technologies)
2	Shedding light on solar technologies – a techno-economic assessment and its policy implications	Techno-economic modelling	Quantitative (and qualitative)	Secondary data (technology data)	Developing and developed countries	cSi-PV, CdTe PV, CSP (CCGT as benchmark)
3	Japan's post-Fukushima Challenge – Implications from the German Experience on Renewable Energy Policy	Comparative case study	Qualitative (and quantitative)	Secondary data (IEA, policy documents etc.)	Japan and Germany	Entire sectoe; focus on nuclear and PV
4	Composting projects under the CDM: Sustainable contribution to mitigate climate change	Multi-criteria analyses	Quantification of mainly qualitative data	Secondary data (UNFCCC)	Developing countries	8 technologies (partly electricity generation, partly other sectors)
5	Climate policy's impact on the rate and direction of corporate innovation activities – a survey of the European electricity sector	Regression analysis*	Quantitative	Primary data (survey)	EU	Entire sector
6	Decarbonising the power sector via technological change – differing contributions from heterogeneous firms	Cluster analysis*	Quantitative	Primary data (survey)	EU	Entire sector

* Paper also contains the development of a theoretical framework

Table 2 shows that the first four papers – those on the macro level – are all based on secondary data. Papers 1 and 2 use cost and performance data of different technologies to compare these technologies via techno-economic bottom-up modelling. Paper 2 contains an additional qualitative comparison. Paper 3, a comparative case study, is partly quantitative and partly qualitative. It draws parallels between the countries and derives a research agenda. Paper 4 is based on multi-criteria assessment in which qualitative and quantitative data is transformed into quantitative comparative indicators. The two papers on the micro level (Papers 5 and 6) each develop a theoretical framework by combining evolutionary approaches with cognitive theory. In both papers statistical analyses of data stemming from an original survey are performed. While in Paper 5 regression analysis is applied, in Paper 6 a cluster analysis is performed. In the following, the different methodologies are explained in more detail.

3.1 Techno-economic modelling

Techno-economic modelling is applied in Paper 1 and 2. For both papers, bottom-up models were developed using secondary data on low-carbon and baseline technologies, i.e., the alternatives most probably built without climate-relevant policies enacted. Both papers are based on the concept of Levelised Cost of Electricity (LCOE) i.e., the cost to generate a unit of electricity over the lifetime of the equipment and under consideration of capital costs in form of a discount rate. “The LCOE equation (see below) allows alternative technologies to be compared when different scales of operation, investment or operating time periods exist.” (Campbell et al., 2009, p. 421).

$$LCOE = \frac{\sum_{t=1}^{n} \frac{Expenditures_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{Electricity\ generated_t}{(1+i)^t}} \qquad \left[\frac{€}{MWh}\right]$$

With $n: lifetime \quad t: year \quad i: Discount\ rate$

The model input can be differentiated into economic (e.g., discount rate, inflation rate, fuel price), techno-economic (e.g., investment cost, running cost) and technical variables (e.g., lifetime, efficiency, load factors etc.) which differ across countries and/or technologies.

In Paper 1, we apply the LCOE concept to 6 developing countries, their baseline power generation mixes as well as cSi-PV (crystalline silicon photovoltaics) and Wind (the LCOE of both RET are calculated for 2010 and 2020). For all calculations, global, i.e., unsubsidised fuel prices are assumed. A search algorithm for the best spots for constructing the new generation capacity is developed and applied. The LCOE of the baseline-mix are deduced of the LCOE of PV and Wind in order to calculate the incremental cost of electricity generation for both low-carbon technologies. By calculating the emission intensity of the baseline and putting them in relation with the incremental cost of PV and Wind, their incremental cost of emission abatement are also computed. Finally, we replace the unsubsidised fuel prices with the real prices in order to calculate the role of fossil fuel subsidies.

In Paper 2 we apply a higher level of data and technology granularity. We compare the three currently leading solar technologies – cSi-PV, thinfilm PV (CdTe) and concentrated solar power (CSP) regarding their LCOE in five different countries (one specific location per country) at the years 2010 and 2020. As the integration of large shares of (intermittent) solar power into the grid may require new storage capacity, we also modelled the levelised cost of electricity storage for the year 2020. In both years we compare the LCOE with a combined-cycle gas turbine (CCGT) running on natural gas. Apart from this quantitative modelling, we compare the three technologies along several other important qualtitative merit dimensions, such as resource bottlenecks for the building material of key components or the water they need in use.

3.2 Comparative case study

Paper 3 is based on a short comparative case study on two countries: Japan and Germany. The Fukushima nuclear disaster may represent a turning point for the Japanese electricity sector. Several parallels are drawn between this new Japanese situation and the German situation ten years ago, before the nuclear phase out was initially enacted. The case study touches on three important areas which are compared for both countries: the sectoral structure, policy objectives and policy making as well as the PV industry status. We analyse the sectoral structure and (potential) transformation of Germany and Japan based on public data on the electricity production by source, literature and policy documents. For the comparison of the policy objectives and policy making, literature on both countries environmental, energy, industrial and economic policy is consulted. We use quantitative data on the photovoltaic industry (net-imports and R&D intensity) to deduce three problems of the strong growth of that technology in Germany.

3.3 Multi-criteria assessment

Paper 4 is mainly based on multi-criteria analysis. After a comparison of different technologies’ CDM project numbers, multi-criteria assessment is used to analyse the different technologies’ contributions to sustainable development. The assessment and its criteria stem from the “Multi-Attributive Assessment of CDM” (MATA-CDM) which is based on multi attribute utility theory (see e.g., von Winterfeldt and Fischer, 1973). MATA-CDM has been developed by Sutter (2003) and is structured along the five step identification of sustainability criteria, defining indicators and their utility function, weighting the criteria, assessing the projects, and aggregating and interpreting the results. Its twelve sustainability criteria (four for each of the three cornerstones of sustainability: society, environment, economics) have been used in other studies to assess sustainability rents of CDM projects (e.g., Heuberger et al., 2007; Nussbaumer, 2009; Sutter and Parreño, 2007). In Paper 4 the simplified MATA-CDM, as described by Nussbaumer (2009)[7] is applied, using the standardized Project Design Documents (PDD) for CDM projects as single source of information. One researcher assessed all projects in order to guarantee that one single standard for assessment was applied. The scores of each project on each dimension were then discussed among the three authors and partly corrected.

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[7] For details on this methodology please refer to his study. Due to the lack of respective data, the scoring function for the criteria fossil energy resources has been modified, resulting in the criteria being qualitative.

3.4 Statistical analyses of survey data

Papers 5 and 6 rely on data from a survey which was conducted by ETH Zurich and Fraunhofer ISI (Germany) in November and December 2009 amongst power generators and technology providers from seven EU countries: Germany, France, Italy, Poland, Slovakia and Spain, plus – in the case of the technology providers – the UK. Subsequent to a series of pre-tests in Austria which served to improve our survey, the final survey was translated in each respective language and a reverse translation was independently conducted in order to guarantee equality in meaning. In order to identify the most suitable respondent each firm in the sample was contacted by phone. To ensure the survey was answered by the senior manager identified, a letter and email with an individual access code was then sent. Follow-up calls were made to increase the response rate. The analyses performed in both studies are based on the answers of 201 firms, 65 power generators and 136 technology providers. This represents a response rate of 13.1% and 12.5% of the population of 496 power generators and 1088 technology providers. The population of power generators in each country was identified based on the EU's Community Independent Transaction Log (CITL) comprising all firms which fall under the EU ETS. The technology provider population in each country was identified on the basis of the KKS power plant classification system of VGB Powertech, the respective European industrial activity classifications (NACE Rev.2) and the firm registry Amadeus.

In Paper 5 a set of hypotheses on the effects of firms' perceptions of climate policy on the rate and direction of their R&D and adoption activities is developed. We use ordinary least square regression analyses in order to test the hypotheses and control for effects of firms' perceptions of other elements in their business environment as well as their characteristics. We conduct six regression analyses, as we are looking at adoption of new technologies by power generators and RD&D of firms that perform R&D, each on the level of total (rate), threatened and aligned (direction) investments, leading to six dependent variables. In order to arrive at consistent regression models, we performed several tests, such as a test for multicollinearity via a correlation matrix and the variance inflation factor (VIF) (Myers, 1990), Harman's one-factor tests for common method bias, a test for heteroscedasticity (Allison, 1999), and a test for normality of the residuals (Q-Q-plots) and the Durbin-Watson statistics (Field, 2009).

Paper 6 analyses the common behaviour changes of firms regarding their R&D *and* diffusion activities. Firms usually take into consideration both activities simultaneously to arrive at a consistent strategy (diffusion activities refers to the production and sales of new technologies by producers and the adoption of the technologies by users). In order to identify different patterns of behavioural change, we perform a cluster analysis considering firms' investment changes along these four dimensions: diffusion of fossil technology, diffusion of non-fossil technology, R&D of fossil technology and of non-fossil technology. Statistically we proceed in two steps. For the cluster analysis we choose a two-step approach: first, a hierarchical cluster analysis (Ward's method) to identify the optimal number of clusters; second, a non-hierarchical K-means analysis to allot the 201 firms to the respective clusters (Hair et al., 2006). In order to compare the clusters along their characteristics we used non-parametric tests for each variable. First we tested whether there are significant differences between any of the clusters via Kruskal-Wallis tests (Field, 2009; Hair et al., 2006). Second, we conduct Bonferroni-corrected Mann-Whitney tests in order to compare clusters in a pair-wise manner (Field, 2009; Hair et al., 2006).

4. Summary of the Papers

While the previous two sections outlined the dissertation's objectives as well as the methods and data used, this section goes more into the details of each paper and highlights their main findings.

4.1 Assessing the cost of PV and wind in six developing countries: Implications for post-Kyoto

Under the Kyoto Protocol, developing countries remain without GHG emission reduction obligations but are addressed by the Clean Development mechanism (CDM) (UNFCCC, 1997). While important, the CDM failed in leveraging private investments in the magnitude needed to limit global warming (Bakker et al., 2011). Therefore, the Cancun Agreement established a financial mechanism administered by the Green Climate Fund (GCF) to support developing countries in greenhouse gas (GHG) emission abatement (UNFCCC, 2011). Yet, besides other issues, two questions remain unresolved. First, how to determine different countries' financial needs for emission abatement (Haites, 2011; Olbrisch et al., 2011), to be financed by developed countries? Second, which instruments are most effective for distributing financial resources in a post-Kyoto regime. These debates are mainly supported by top-down numbers. While such numbers are important for approximating total financial needs, more detailed data is needed to account for costs differing strongly across countries and technologies (Bakker et al., 2011; Schneider et al., 2010). We address this gap by analyzing the incremental costs of Wind and photovoltaics (PV) – two technologies with abundant natural potential – in six developing countries. More specifically, we apply a consistent methodology comprising the following steps: (1) calculation of the levelised costs of electricity generation (LCOE) of the baseline power mix, (2) calculation of LCOE of PV and Wind, (3) derivation of the incremental costs of both electricity generation and emission abatement, (4) analysis of the effects of fuel subsidies on these costs. We conclude with implications for the aforementioned debates on financing needs and instrument choice.

The results of the first step show the large heterogeneity between the countries' marginal baseline LCOE. Step two reveals that the LCOE of PV are generally much higher than those of wind and, despite large cost reductions in the next ten years, will continue to exceed wind by far. Large scale PV is thus a rather long-term option in developing countries, whereas wind technologies should be diffused quickly due to their significantly lower cost and smaller cost reduction potential. The third step of our analyses (see Figure 3) shows that PV has high incremental cost in all countries (which might be different in decentralised applications where the baseline LCOE can be very high). Regarding wind, three groups of countries can be identified. In India and Thailand the incremental costs are very high. The incremental costs in Brazil and Egypt are close to zero. In Kenya and Nicaragua, strikingly, the incremental costs of wind are highly negative as the high baseline LCOE by far exceed the wind LCOE. At this point, the role of the subsidies comes into play, which we treated in the fourth step. Our results indicate that fuel subsidies can strongly distort the competitiveness of RET which are relatively close to competitiveness.

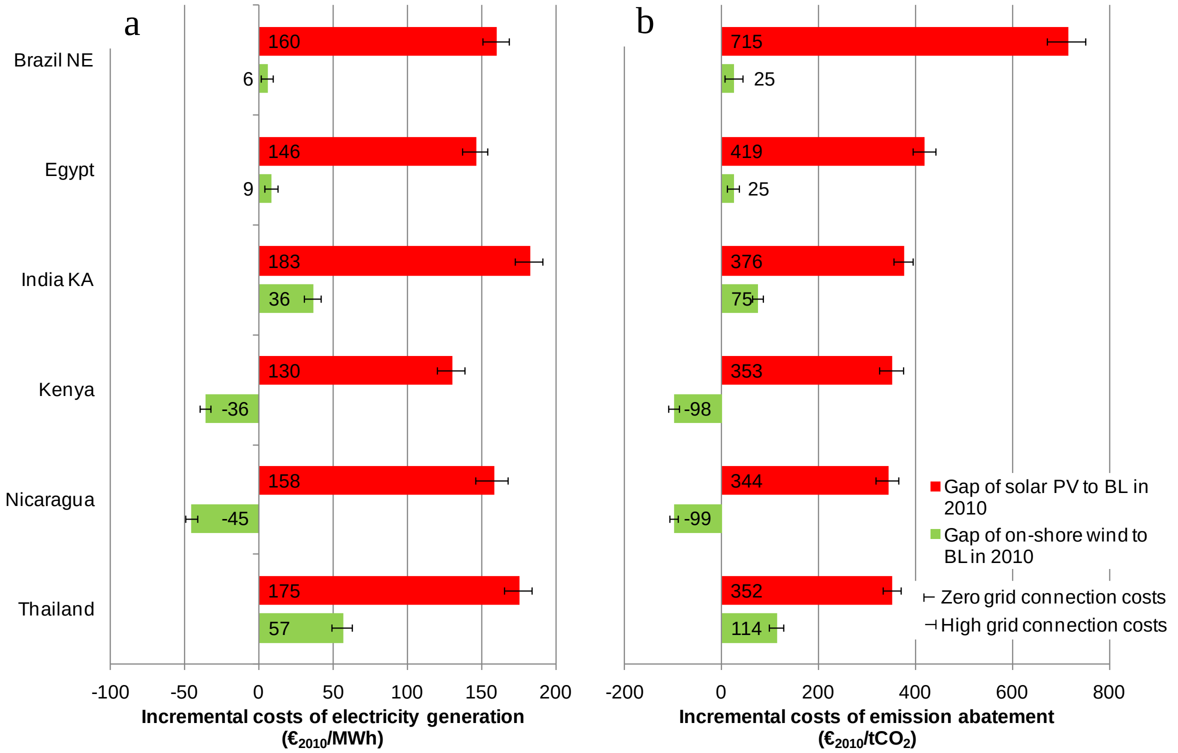


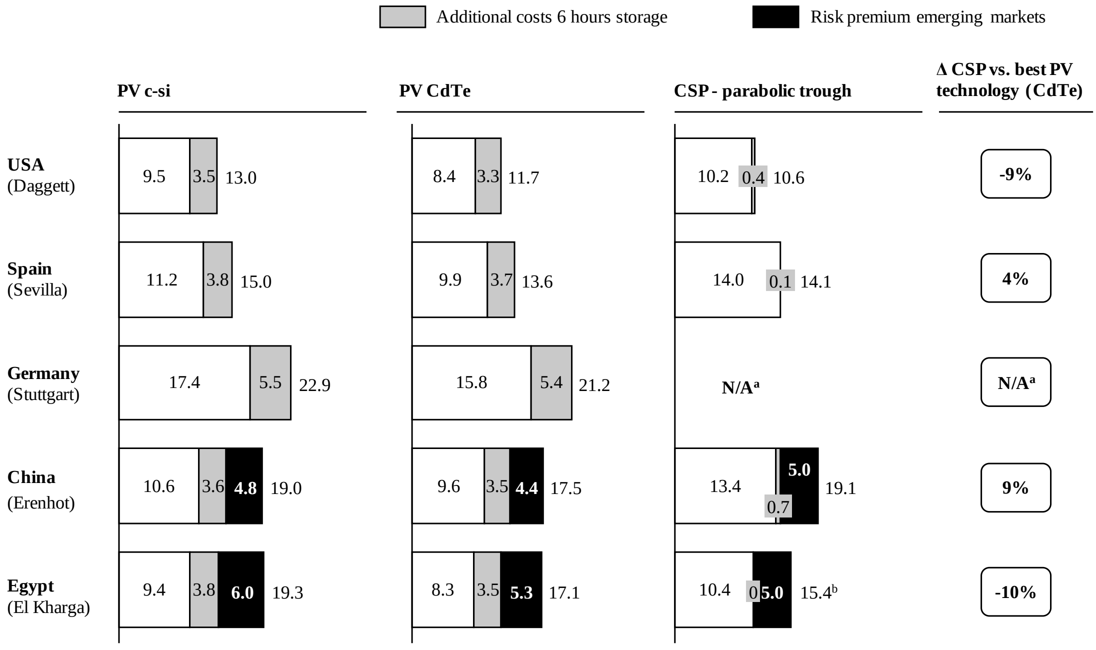
Figure 3: The incremental costs of electricity generation (a) and emission abatement (b). The red bars depict the incremental costs of solar PV, the green bars those of wind. Again, the influence of the grid-connection costs is depicted by the black stripes. In india and Brazil our analyses are limited to certain regions (NE: north-eastern grid region; KA: federal state of Karnataka)

From these results we derive two policy recommendations addressing the above mentioned questions. First, the finding that the incremental costs strongly differ between specific country-technology combinations suggests that differentiation should be done on the basis of such country-technology combinations rather than by separating technology and country, as is currently being debated (Bakker et al., 2011). While doing this under the CDM would further increase its already high transaction costs, NAMAs can very well address single country-technology combinations without requiring excessive administrative expenditure. Second, the detected role of subsidies reveals that tackling the baseline is a key issue for future climate policy. While integrating incentives to address the baseline in the CDM seems intricate, NAMAs can combine support instruments with measures addressing the baseline and thereby strongly decrease the incremental cost of abatement technologies.

4.2 Shedding light on solar technologies – a techno-economic assessment and its policy implications

While currently very expensive (compare 4.1), solar power technologies will have to become a major pillar in the world’s future energy system to combat climate change and resource depletion. A wide set of solar technologies is available in the field of PV and concentrating solar power (CSP) with differing performance characteristics. However, which technology is and will prove most viable in our electricity systems is heavily contested among scholars and industry experts (Fthenakis et al., 2009; PricewaterhouseCoopers, 2010). Therefore, a comprehensive comparative assessment of solar technologies along the key quantitative and qualitative competitiveness criteria is needed. While the competitiveness of solar power generation differs by technology, time and location the extant literature lacks a holistic assessment of solar power based on these three dimensions. We address this lack by focusing on the following research question: What is the competitiveness of leading solar technologies depending on time and location?

Based on a literature review and detailed techno-economic modelling for 2010 and 2020 in five locations, we provide an techno-economic LCOE assessment of the three currently leading large-scale solar technologies (cSi PV, CdTe PV and CSP) and compare them with a fossil benchmark. We complement our model by analysing the technologies on important qualitative merit dimensions.



a DNI in Germany (~2 kWh/sqm per day) is not sufficient to effectively operate a CSP plant. Scholars usually cite a threshold of 5 kWh/sqm per day
b 15.6 excluding storage

Figure 4: Levelised cost of electricity in 2020 by country, EUR$_{2020}$ cents/kWh

Our results show that in 2010 all technologies cannot compete with the fossil benchmark (a combined cycle gas turbine). In 2020, however, solar LCOE in the US and Spain approach parity with CCGT. With regard to the solar technology comparison in 2010, in all locations PV CdTe ranks 1st, PV c-Si 2nd and CSP 3rd, with PV c-Si being 10%-13% more expensive than PV CdTe and CSP being 25%-45% more expensive than PV CdTe. In 2020 (compare Figure 4), driven by the integration of storage, CSP outperforms PV in two locations (US, Egypt). The delta between CSP and PV CdTe ranges from -10% to 9%. The LCOE difference between PV CdTe and PV c-Si remains stable with PV c-Si being

10% to 14% more expensive. This means, no clear winner between PV and CSP could be found, which also applies to the qualitative dimensions.

In sum, our results imply that in order to foster and exploit the 'solar option', which is not competitive, yet, smart policy action on global and national levels is required. Essentially, four aspects must be addressed that relate to the main variables analyzed above. First, further policy support should incentivize innovators to exploit the technology-specific learning potentials in the field of PV and CSP technologies. Second, capitalizing on the solar resource available in sunbelt countries is crucial in order to efficiently deploy large-scale solar technologies. Third, policymakers can increase the efficiency of policy support by incentivizing investors and technology providers to exploit location-specific strengths of PV and CSP technologies. Fourth, due to the substantial cost, which is still involved in supporting these technologies at present, policymakers need to assess whether there are strategic co-benefits that enhance the political feasibility and stability of such support.

4.3 Japan's post-Fukushima Challenge – Implications from the German Experience on Renewable Energy Policy

Writing this paper was triggered by an external event: the accident at the Fukushima nuclear power plant in Japan in the wake of a 9.0 magnitude earthquake and tsunami on 11 March 2011. The Japanese electricity sector is facing serious challenges in the aftermath of this nuclear disaster, making it to a potential turning point for the country's energy future. The current draft of Japan's 'Basic Energy Plan', adopted in 2010, targeted the share of nuclear power to surge from roughly 30% to 50% by 2030 – a goal that seems unthinkable now, with then prime minister Naoto Kan, proposing a nuclear phase-out until 2050 on 30 July 2011. The role of renewable energy technologies, which have so far only played a minor role in Japan's electricity generation mix, might rise drastically. The government indicated a plan aiming to increase their contribution to power supply from ca. 8% to 20% by 2020. This is a share that even ambitious plans did not envisage before 2030. In fact, the 20%-target of the Japanese government implies an electricity sector transformation very much similar to the changes that took place in Germany in the last decade (compare Figure 5). Hence, we argue that some of the lessons learned in Germany might prove valuable for the steps Japan considers taking.

While the policy instruments leading to such rapid diffusion of RET in Germany – mainly feed-in tariffs (FIT) – are often seen as success story, three interrelated legitimacy issues have fuelled a public and scientific debate about the scheme's future (e.g., Frondel et al., 2008b): (i) mounting payment commitments; (ii) a low research intensity in the industry; and (iii) rising net imports. While it is likely that these issues will do only little to cloud the prospects of Renewables in Germany (particularly since the government announced a phase-out of nuclear power until 2022 as a very consequence of the Fukushima accident) this is supposedly different in Japan.

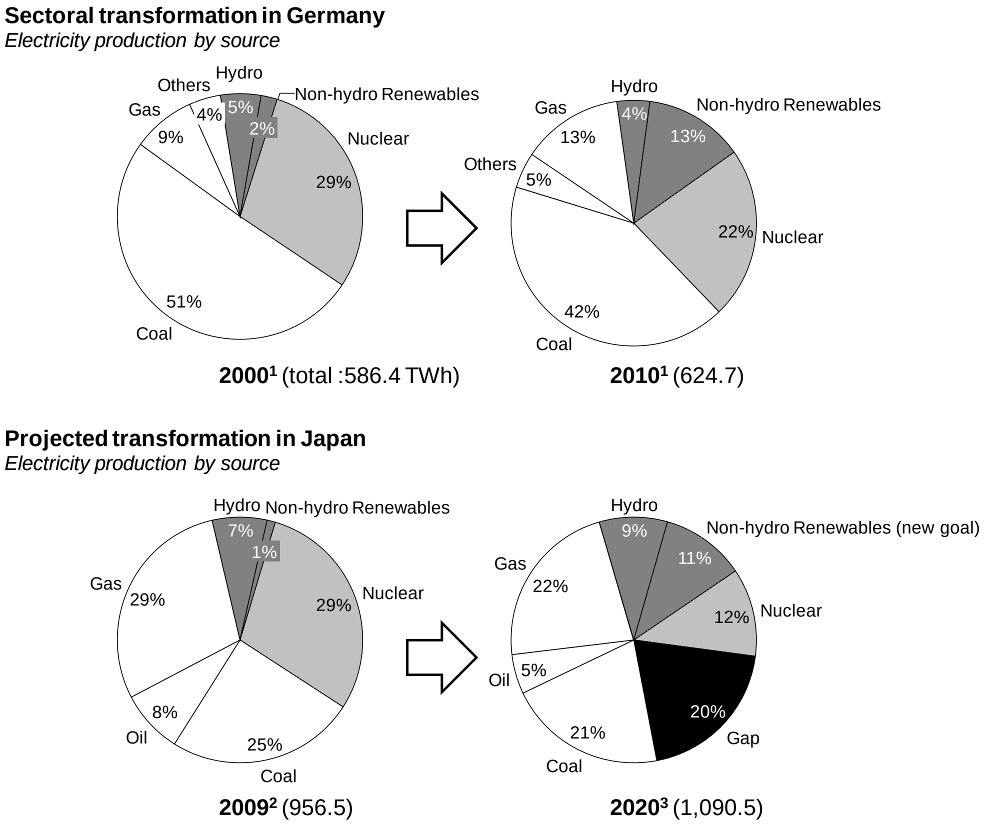


Figure 5: Comparison of German energy sector transformation in 2000-2010 with challenges faced by Japan in period 2009-2019; [1]data from BMWi (2011); [2] data from FEPC (2011); [3] data for nuclear power from projection by Iida (2011), non-hydro renewable contribution assumed to fulfill 20 % goal announced in June, 2010; other data from projection for 2019 by FEPC (2011). Note that the gap stemming from shut-down of nuclear facilities requires additional energy saving, extension of nuclear power plant life-time, or investments in fossil fuels above the business-as-usual scenario.

There are three reasons to believe that the current situation and the idiosyncrasies of Japanese politics make it imperative for Japan’s policymakers to pay special attention to the legitimacy issues arising for the German FIT. First, Japan will probably rely more on PV, the most expensive commercially available form of power generation than Germany. Second, the imbalanced energy policy responsibilities (the powerful Ministry of Economy, Trade and Industry (METI) is almost exclusively responsible for electricity regulation) render economic objectives distinctively important in Japan. Third, the advances of the PV industry outside of Japan (especially Chinese companies are gaining competitiveness) might render these economic objectives distinctively difficult to fulfill. Energy policy researchers should address these challenges. To this end we propose a research agenda.

Japan’s situation is a salient example for a general need, faced by many developed and developing countries: to design integrated national policies that combine the economic benefits of energy or industrial policy and the environmental benefits of climate, renewable energy, or transition policy (Alkemade et al., 2011; Bazilian et al., 2010). In this regard, we need to understand whether demand-side measures are on their own sufficient to incentivize significant technical change, and whether strict domestic regulation is related to positive export performance. While theory generally assumes positive effects of demand-pull measures on diffusion and innovation, cases such as the PV FIT in Germany suggest that there are important context and technology-specific factors that influence the effects of demand-side measures. Hence, for the case of Japan, transferring the positive experience from the Top-Runner approach (a program aiming at efficiency of end-use appliances) to an adapted FIT for PV might be an option to create a more balanced regulation of the demand and supply sides. Researchers should analyze the compatibility of such scheme with WTO rules.

4.4 Composting projects under the CDM: Sustainable contribution to mitigate climate change

The CDM aims to not only reduce emissions but also to “assist Parties not included in Annex-I in achieving sustainable development” (UNFCCC, 1997, p. 11). This paper elaborates on this second goal. In order to move towards sustainability a consensus of three different interests, namely economic, social, and natural capital must be achieved (United Nations General Assembley, 2005). We decided to not completely focus on the energy sector in this paper but to compare waste sector, household and electricity sector projects. In fact, the focus of the study is rather on the waste sector, where the usage of the waste for energy purposes (biogas, landfill-gas) competes with agricultural purposes (composting) (Barton et al., 2008). Based on a multi-criteria assessment, we compare eight best-in class project types with regards to their contribution to sustainable development on twelve dimensions. These project types are: two types of composting projects, landfill gas and biogas to power, Biomass to energy (heat and/or power), household energy efficiency, solar cooking and wind power.

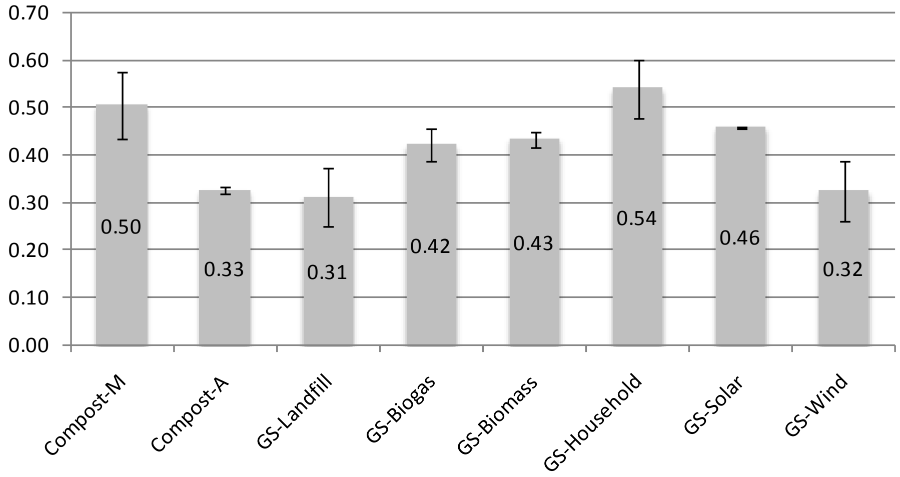


Figure 6: Sustainable development impact of CDM projects: Comparison of different project types. The error bars indicate the standard deviation.

Our results – the average scores across all sustainability dimensions are depicted in Figure 6 for each project type – show that all project types analysed have a positive sustainability impact. The highest average score was reached by household projects, followed by composting of municipal solid waste (Compost-M), solar cooking, biomass, and biogas. Lower scores have been attached to composting of agricultural leftovers (Compost-A), wind and the lowest for landfill gas to power projects. While for instance wind projects do not compete with other project types for the same resource, such competition is the case with regards to the resource waste.

For the case of municipal solid waste, our analysis shows that using this resource with composting projects will probably have higher sustainability contributions than using it for electricity generation in landfill-gas to power projects. The paper proposes a list of criteria to assure high sustainability contributions of such composting projects. Another finding of the paper is that composting project are financially dis-incentivised by the UNFCCC due to the emission reduction calculation methodology. Based on our results, we recommend modifying the methodology for the calculation of the emission reductions and thereby increase the competitiveness of composting projects. This could raise the potential of the CDM to contribute to sustainable development. Furthermore, sustainability labelling organisations should make composting projects eligible for their sustainability labels.

4.5 Climate policy’s impact on the rate and direction of corporate innovation activities – a survey of the European electricity sector

This paper aims to assess the impact of climate policy on technological change by focusing on the changes it causes in the rate and direction of corporate innovation activities. In this regard, two research gaps exist. First, a framework “which takes into account the interplay between relevant variables influencing environmental technological change and all the stages of this process” is lacking (del Río González, 2009, p. 861) . Second, there are only few quantitative empirical studies on the effect of climate policy on the innovation activities of firms (Ellerman et al., 2010). We address both lacks by first proposing a framework, for which we use concepts from evolutionary economics and complement them by organisational theory, namely a cognitive perspective, in order to consider a firm’s perception of its business environment (Anderson and Paine, 1975).

In this framework, we distinguish emissions trading – more precisely the EU ETS – and long-term emission reduction targets and consider further determinants external and internal to the firm We differentiate the rate and direction (by distinguishing emitting, i.e., threatened and non-emitting, i.e., aligned technologies) of research, development and demonstration (RD&D) as well as technology adoption. Furthermore, we consider relevant actors across the value chain, namely users and producers of technology (Lundvall, 1985; von Hippel, 1976).Two levels are distinguished in our framework (see Figure 7): the business environment external to the firm, and the firm itself with its innovation characteristics and activities. Changes in the rate and direction of these activities are determined by climate policy, context factors, and the firm characteristics. A firm perceives the variables form the business environment through a cognitive lens.

Based on this framework, we derive hypotheses, which we test for the European electricity sector. To this end, we perform a regression analysis based on survey data of firms in seven EU countries.

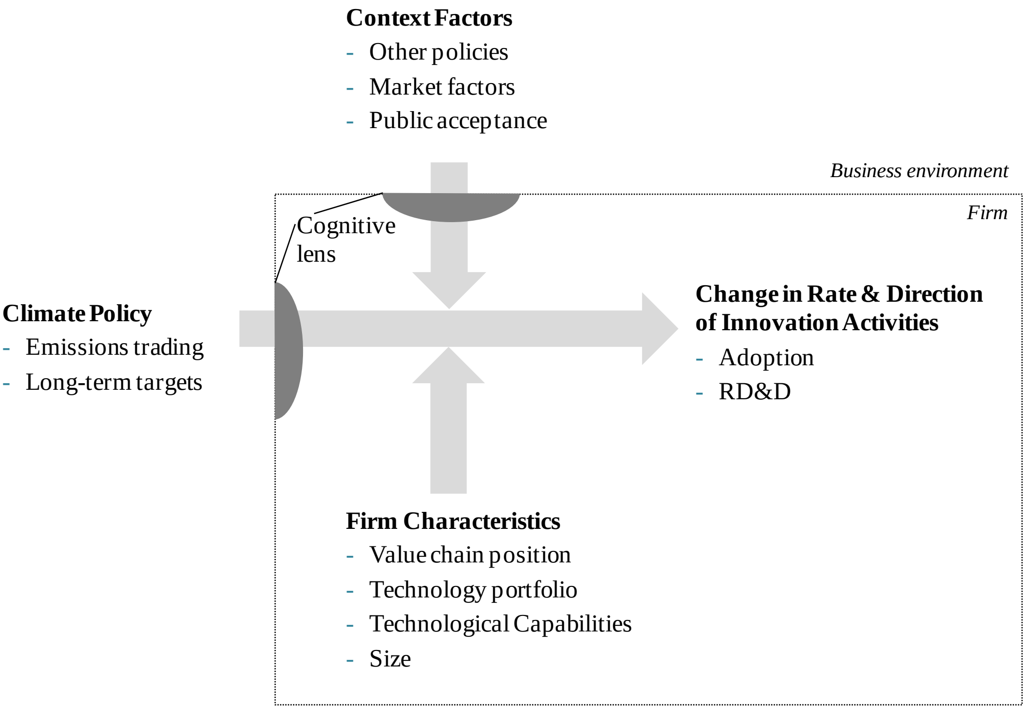


Figure 7: Theoretical framework

The descriptive results highlight that on average power generators have moderately increased the adoption in total and the adoption of threatened technologies in the last 5 years. Investments in new aligned plants experienced a stronger rise. Regarding RD&D, total and aligned activities experienced a higher increase than the moderately augmented threatened RD&D activities. Our regression analysis yields three important findings: First, our results show that the EU ETS in its early phases (ETS 1&2) neither triggered investments in the adoption of aligned technologies nor in RD&D. The only effect we do observe, namely the increased adoption of threatened technologies, undermines the goal of substantial GHG emission reductions. Policy makers in regions which also plan to introduce emission trading, e.g., China (United Nations, 2011), should be aware of the potential counterproductive consequences of a too lax emission trading design. In Europe, where it is too late to adjust the initial EU ETS design now, the EU should guarantee a minimum stringency for phase three (ETS 3). Second, our results show the importance of technology-push policies as well as long-term targets for RD&D. The latter have an orienting function (especially important in the power sector with its large R&D time constants) and might, if stringent and credible, indicate a long-term paradigm shift. For policy makers this implies that RD&D support and long-term targets should be part of an integrated mix which complements emission trading. Third, our study reveals that neither ETS 1&2 nor ETS 3 was capable of triggering increased aligned technology adoption. Only RET- pull policies had this effect. Therefore, these policies are an element of the policy mix essential to avoid a lock-in into currently cheaper technologies positively affected by emission trading which, however, might come at higher cost and/or lower emission reductions in the long-run (del Río González, 2008).

4.6 Decarbonising the power sector via technological change – differing contributions from heterogeneous firms

When analysing technological change, evolutionary scholars stress the role of firms and their heterogeneity (Dosi, 1997; Nelson and Winter, 1982). Technological change at the firm level comprises two things: research and development (R&D) and diffusion activities. Thus far, empirical studies looking at the effect of climate and climate-relevant technology policies on technological change using firm level data are either of qualitative nature (e.g., Cames, 2010; Ikkatai et al., 2008; Rogge et al., 2011b), focus on a single innovative activity i.e., R&D or diffusion (e.g., Laurikka and Koljonen, 2006), and/or analyse both activities separately (e.g., Rogge et al., 2011a; Schmidt et al., 2011). However, firms typically consider both dimensions simultaneously in order to arrive at a consistent investment decision (Lavie et al., 2010; March, 1991). Hence, there is a lack of analyses looking at firms' integral *behaviour*, i.e., the totality of a firm's decisions on how to devote resources to R&D *and* diffusion activities of different technologies.

Of particular interest for policymakers is how firms adjust behaviour in new regulatory environments. Such information may be used to answer the question of whether readjustments of the policy mix are needed. Firms are expected to change their behaviour in different ways; i.e., a population of firms is expected to exhibit *behavioural heterogeneity* (Nelson, 1991). Observing behavioural heterogeneity, i.e., whether firms change their behaviour to which extent and how, can provide quick feedback on the state of the acceleration and redirection of technological change. The behavioural heterogeneity is to a large extent explained by the different characteristics of the firms, i.e., their *characteristic heterogeneity* (Nelson, 1991). Should the findings on the behavioural heterogeneity show a need for policy readjustments, information about the characteristic heterogeneity of firms is also valuable for policy makers to tailor actor-specific instruments. By covering both aspects, the behavioural and the characteristic heterogeneity, we address the following research question:

How do firms with diverse characteristics differ regarding their contributions to low-carbon technological change in the power sector?

We analyse original survey data on power generators and power generation technology providers in seven European countries. First, we perform a cluster analysis to show how the innovation behaviour changes in the sector differ. Second, we compare these clusters regarding their attributes and their policy perceptions.

Our analysis resulted in seven clusters (see Table 3) and highlight how differently firms have changed their innovation behaviour. Three patterns can be identified: firms not strongly changing their innovation behaviour, firms redirecting their behaviour in a fossil direction and firms accelerating and/or redirecting their innovation behaviour in a manner that they contribute to low-carbon technological change, yet, in a very different manner.

Table 3: **Changes in innovation behaviour.** Cluster centres and size

			BAU	Fossil Diffusion	Clean Focus	Overall Diffusion	Overall Innovation	Clean Shift	Fossil Exit
Cluster Centers	R&D	non-fossil	0.15	0.07	1.11	0.05	1.36	1.50	-0.10
		fossil	0.06	0.27	0.00	0.15	1.25	-1.90	0.00
	Diffusion	non-fossil	0.17	-0.20	1.78	1.56	0.97	1.52	0.27
		fossil	0.02	1.67	0.00	1.43	0.77	-0.40	-1.55
Number of companies			80	15	59	17	15	5	10
% of companies			39.80%	7.50%	29.40%	8.50%	7.50%	2.50%	5.00%

The cluster centres can theoretically vary from -2 via 0 to +2 indicating whether the respective activity was strongly decreased, kept constant or strongly increased.

The fact that about 40% of the firms do not contribute to an acceleration and redirection of technological change and another almost 8% contributes to a redirection to the fossil direction is an important information for policy makers. These large inertia and controversial innovation behaviour changes cast into doubt whether the current policy mix is able to trigger an acceleration and redirection of technological change in a magnitude needed to meet the 450ppm target. With respect to their characteristic heterogeneity, several clusters differ strongly regarding both the firms’ attributes and their policy perceptions. While the BAU cluster seems to contain very heterogeneous firms (the variance of the distribution is quite high), other clusters show strong peculiarities. This of course has implications for policy makers and enables us to derive policy recommendations for each group of firms.

5. Conclusions

Global climate change makes ample and quick transformations of energy related sectors an imperative. As the endogenous rate and direction of technological change is insufficient to address the urgency of the problem, policy needs to and already has become active. At the same time, public money to be spent for this purpose is limited and the economy depends on cheap energy services (Rosenberg, 1982). As electricity generation is one of the key sectors for climate change and its mitigation, it is the objective of this thesis to support policy makers regarding the question of *how to induce technological change towards strong decarbonisation of the electricity sector*.

In the following, the dissertation's main contributions, policy recommendations and proposed ideas for future research are outlined.

5.1 Contributions

The contributions of this thesis can be classified in three groups. First, a contribution is made by applying an analytical and methodological pluralism. Scholars have stressed that handling problems of high complexity – and the present research question certainly features high complexity – necessitates a methodological pluralism (e.g., Little, 1999; Norgaard, 1989). The applied pluralism allowed us to address different sub-aspects of the research question with the appropriate methodology and level of analysis in each case. Referring to Kemp and Pontoglio's (2008) paper, the thesis thereby tries to avoid 'judging the elephant like one blind man'. Two analytical levels are introduced: a macro- and a micro-level. While most studies analysing climate-relevant policy and the power sector are positioned either on the macro- or the micro-level, this thesis takes an integrative approach and thereby tries to address the high complexity that underlies the research question. The macro-level is concerned with the amount and form of policy incentives. The micro-level refers to the actors responsible for an acceleration and redirection of technological change. Furthermore, the dissertation uses several methods and different data sources. Despite all pluralism, each paper aims at the same target: to provide better information for policy makers on how to induce low-carbon technological change. A combination of the findings of the different papers leads to a combined set of policy recommendations (see below).

Second, a theoretical contribution lies in the combination of organisational cognitive theory with evolutionary innovation theory (Papers 5 and 6). Cognition is an implicit concept of the latter as according to evolutionary theory actors' "limited *understanding* [...] of the environment in which they are embedded" shapes their actions and thereby technological change (Dosi et al., 1997, P. 1540). However, only recently have authors started to make the role of organisational cognition in technological change more explicit (e.g., Kaplan and Tripsas, 2008; Nooteboom, 2009). This dissertation contributes to this new stream by integrating cognition into the analysis of the role of policy in firms' decisions relevant to technological change through the proposition of two frameworks and by formulating a set of testable hypotheses (Paper 5). By relating these frameworks to data and statistical analyses we show that they are useful in terms of improving our understanding of policy and technological change.

Third, the dissertation makes several empirical contributions. The analyses on the macro-level (Papers 1 to 4) provide new, detailed data on low-carbon technologies' costs and other dimensions. Only recently has one of the IPCC's lead authors, Prof. Edenhofer (2011), identified "a striking dearth in reliable peer-reviewed data on what it costs to generate renewable electricity and what determines those costs". The new data we provide allow for a better understanding of necessary policy support as they consider technology differences, such as the different stages in which technologies are in the technology cycle (Tushman and Rosenkopf, 1992) and the associated differences in learning dynamics and cost reduction potentials over time. Highlighting the role of country differences as well as other sustainability dimensions of technologies further improves the understanding of technologies' varying performances in different contexts.

The analyses on the micro level (Papers 5 and 6) provide new data on the effects of currently enacted climate-relevant policies. While "theoretical arguments are abundant and clear [...], empirical evidence on the predicted effects [of the EU ETS] is scant" (Ellerman et al., 2010, p. 289). We address this gap by collecting new data through an original survey of several firms along the value chain, thereby doing justice to the supplier dominance in the power sector (Cames, 2004; Pavitt, 1984). The statistical analyses unveil potential for improvements in the current policy mix. In sum, all three contributions improve our ability to make recommendations for policy makers.

5.2 Policy recommendations

Climate policy stands at the crossroads. With the Kyoto Protocol expiring at the end of 2012, a new and more effective global framework is needed. While in the Copenhagen Accord and the Cancun Agreement many countries agreed upon certain steps, several important questions regarding future policy mechanisms remain unresolved. Depending on the outcome of the post-Kyoto negotiations, the EU might (have to) change its rules for phase three of the EU ETS (starting in 2013) and introduce other policy instruments.

The policy recommendation section is divided into four topics. First, we discuss two aspects (see also Sections 1 and 2) which are currently highly debated globally (Hoehne, 2011; Olbrisch et al., 2011): (i) the type of incentives needed for the low-carbon transition and (ii) the required amount of these incentives. Both aspects are closely related to the choice of policy instruments and their design (see Sections 1 and 2). In our policy recommendations regarding instruments and design, we differentiate (iii) EU countries from (iv) developing countries, as the policy challenges differ strongly for these countries (see Section 1).

Which type of incentive?

The main instrument put forward by the Kyoto Protocol is emissions trading, a technology-neutral demand-pull policy (Azar and Sandén, 2011). The resulting carbon price is intended to incentivise a low-carbon transition by reducing the relative competitiveness of emission-intensive technologies compared to low-carbon technologies. However, this dissertation's results cast doubt on the effectiveness of mere emissions trading, as promoted by several (neo-classical) scholars (e.g., Böhringer and Rosendahl, 2009). As reasoned by other researchers (e.g., Azar and Sandén, 2011; del Río González, 2008), our results suggest that a carbon price (whether resulting from a tax or an emission trading system) would lead to lock-ins of second best technologies, i.e., technologies whose emission reductions might not be sufficient or whose cost might be higher in the long run. This is the case as many low-carbon technologies with high technical potential are not "reached" by such instruments yet. This is shown via modelling on the macro- (Paper 1 and 2) and by the statistically tested effects of various policy instruments on the micro-level (Paper 5). Assuming the price is set at a realistic level – meaning a level which would not pose serious threats to our global economy – these technologies remain too costly for a carbon price to lift the cost of emitting technologies beyond their own. Hence, other instruments are needed to complement emission trading in a consistent policy mix (see also: Azar and Sandén, 2011; del Río González, 2008; Goulder and Parry, 2008; Rennings, 2000; Sagar and van der Zwaan, 2006).

In order to increase private R&D in technologies which are further away from competitiveness beyond the limited increases resulting from the introduction of a carbon price instrument, technology-push policies (e.g., in the form of R&D subsidies for these technologies) are essential (Papers 2 and 5). In order to additionally facilitate production-based cost reductions technology-specific demand-pull policies (such as preferential feed-in tariffs for RET) are crucial (Papers 2, 3, 5 and 6). Finally, our findings highlight the role of long-term targets in the policy mix (Paper 5 and 6). They are an incentive as they have an orienting function for firms and should be congruent with the underlying instruments.

How much incentive?

The required level of incentive that is to be provided by these additional instruments needs to be known in order to limit public spending and avoid over- or under-incentivising single technologies. To this end, good information on the incremental costs of low-carbon technologies, i.e., their cost surplus compared to baseline technologies, is instrumental. Three important findings of this thesis regarding low-carbon technologies' costs point to the need for differentiated policy support: the role of technology differences, country differences and time.

Regarding technology differences, our analyses show that some low-carbon technologies are relatively close to competitiveness (wind) while others are still further away (solar), supporting the call for strongly differentiated technology-specific policy support instruments (Papers 1 and 2). Furthermore, power generation technologies are integrated into "open assembled [infrastructure] systems" (Tushman and Rosenkopf, 1992, p. 330) and depend on complementary technologies, such as storage, that enable their large scale diffusion (Rosenberg, 1982). Policy needs to also factor-in the support that these technologies might need, as the cost of these potentially decisive technologies can be very high and needs to be reduced via learning and economies of scale (Paper 2). As policy certainly has more targets than climate change mitigation, political support in developing countries should also depend on the contribution of different technologies to sustainable development (Papers 2 and 4).

Regarding country differences, our results show that the incremental costs of low-carbon technologies vary strongly across countries and therefore differ for each specific country-technology combination. Therefore, policy makers should differentiate neither between technologies nor countries individually but design instruments that address specific technology-country-combinations (Paper 1). Besides the varying natural resources, which are an important cost determinant, discount rates in riskier countries strongly increase the cost of low-carbon technologies (Papers 1 and 2). Therefore, addressing the discount rate with respective instruments (see below) can reduce the incremental cost and thereby influence necessary policy support. Selecting countries with the lowest support needs for the diffusion of the technology could reduce the total global financial support necessary to harness the production-based cost reductions (Paper 2). A further very important country-specific determinant for the incremental cost of low-carbon technologies is the financial baseline, i.e., the cost of the technologies against which the low-carbon technologies have to compete. In developing countries in particular, these conventional technologies are often highly subsidised, thereby “artificially” distorting the competitiveness of low-carbon technologies and increasing their support needs. A very important assignment for the post-Kyoto agreement is therefore to reduce and in the medium-term completely abolish fossil fuel subsidies (Paper 1).

Time matters in two respects. First, we show that technologies currently exhibiting high costs have the potential to become competitive in the future: Provided that policy support is granted, learning and economies of scale can reduce cost strongly (Paper 1 and 2). The height of the incremental costs is therefore very dynamic, making an adjustment of policy support over time important (Papers 2 and 3). For instance, while solar technologies are currently still far away from competitiveness, they will get much closer to it in about 10 years. Therefore, in order to pare policy support down to the necessary minimum, the height of policy support must be as dynamic as the achieved cost reductions. Above that, well-intentioned policy instruments providing too much support can have adverse effects by disincentivising R&D (Paper 3). Second, the effect of policy support on a project does not only depend on its absolute amount but also on how the support is distributed over the project’s lifetime (Paper 4). The delay of payments can deteriorate the supportive effect and thus should be avoided, especially in countries with high discount rates.

How to make the EU policy mix more effective?

The first element of the European policy mix to be improved is the EU ETS itself (Papers 5 and 6). While the fact that Germany recently decided to phase out nuclear power plants by 2022 is expected to cause rising allowance prices (Point Carbon, 2011), tightening the emission caps (in accordance with a raised emission reduction target) would further increase the stringency of the ETS. Above that, the auctioning of emission rights, as provided for in the power sector from 2013 onwards (ETS phase 3), is one way of better incentivising investments in aligned technologies (Hepburn et al., 2006). Price floors that signal a certain minimum stringency and thereby reduce regulatory uncertainty could be an additional measure (Hepburn et al., 2006; Neuhoff, 2011a). A very recent analysis concluded that the potential pitfalls of such price floors can be avoided by smartly designed floor mechanisms (Wood and Jotzo, 2011). The free allocation methods of those member states which are subject to exemptions from full auctioning from 2013 onwards should be strictly supervised by the EU in order to avoid similar effects as observed under the early phases of the EU ETS (see below). Furthermore, within these remaining allocations, certain rules should incentivise firms which are pro-active in taking strong GHG emission reducing measures via adoption and/or RD&D[8]. The European Commission's thoughts on an "innovation/ technology accelerator" (European Comission, 2010, p. 75) for industrial sectors head in this direction and might also be applied to the power sector.

The policy elements accompanying the EU ETS should also be adjusted. First, in the power sector, which has very long time constants regarding R&D and construction, long-term targets serve as important points of reference (Papers 5 and 6). In order to provide good orientation and increase the predictability of climate policy, an important aspect for corporate investment decisions (Engau and Hoffmann, 2011; Hoffmann et al., 2009), LTT should be solid and well communicated. Besides clearly set (and well communicated) European emission reduction targets[9], the approval of an ambitious post-Kyoto agreement could provide such orienting function. Furthermore, LTT need to be congruent, i.e., in accordance, with the existing policy instruments. In order to avoid incongruence, "ambitious and realistic" LTT "at the limits of the capacity that is technically feasible for a country" (Jänicke, 2011, p. 18) should be formulated first. Based on these targets, it is crucial that instruments are installed in order to make the LTT credible (Paper 5).

Second, to this end technology-push policies, i.e., R&D subsidy programmes, which were found to be very important determinants for firms' R&D decisions, are to be oriented very much along the long-term targets (Papers 5 and 6). This means that R&D in fossil technologies should only be supported if the respective R&D activities promise substantive emission reductions. Low-carbon technologies ought to be supported if their cost reductions depend strongly on learning through research (Papers 2 and 3).

Third, to increase the production-based cost reductions technology-specific demand-pull instruments should be extended (Papers 1, 2, 3 and 5). However, in order to avoid setting wrong incentives they should be made dynamic (see above) and could be combined with incentives for R&D for those technologies for which research bears high cost reduction potential (Paper 3). A consistent policy mix

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[8] Research, Development and Demonstration

[9] Instead of the long lasting debate on whether to increase the targets from 20 to 30% by 2020 (The Guardian, 2010), an early and unequivocal decision for the more ambitious target would have been a clear signal to the relevant firms.

ought to also target technologies that enable the large-scale diffusion of low-carbon technologies, such as grid and storage technologies (see above and Papers 2 and 5).

Fourth, policy makers in the EU should factor-in that some firms which are not able to adapt to the newly shaped business environment will decrease in size or even go bankrupt (Paper 6). Policy needs to withstand lobbying pressures from these firms. At this point the role of the EU is vital as it can withstand the expected lobbying pressures from these companies much better than national governments.

Countries that are planning to introduce an emission trading system (independent of whether these are developing or industrialised countries) should try to avoid the mistakes made under the first phases of the EU ETS: We find that the allocation rules in these two ETS phases led to an increase in investments into fossil technologies, increasing the lock-in into these technologies in the long-run (Paper 5). It might be necessary to begin a regulation with a lax design (Ellerman et al., 2010). However, while such a policy having no effect can be borne, adverse incentives as provided for in the early EU ETS phases should be avoided.

How to improve policy in developing countries?

For developing countries as well as the industrialised countries supporting them, our findings have important implications regarding the design of a post-Kyoto agreement. The Kyoto Protocol's Clean Development Mechanism represents a single carbon price instrument. Nationally Appropriate Mitigation Actions (NAMAs), ”a set of policies and actions tailored to the circumstances of individual countries” (Hoehne, 2011, p.32) which can include several instruments, are being considered as an alternative to a (reformed) CDM. Our results (Paper 1) suggest that NAMAs have a much greater potential to effectuate the necessary transitions. They can combine several instruments, which on the one hand provide country-technology-country-specific support for low-carbon technologies in a consistent and congruent policy mix and on the other hand address the baseline, e.g., via the reduction of fossil fuel subsidies. Thereby, they can reduce the global cost of climate change mitigation and govern technological R&D and diffusion in accordance with country specific needs, potentials and objectives. Developing countries should perform assessments regarding which low-carbon technologies best suit these potentials, objectives and needs. These assessments should not only consider costs and GHG emission abatement potential but also other important dimensions necessary for the sustainable development of these countries (Papers 2 and 4). Based on these assessments, certain key technologies are to be selected and respective support policies formulated, which ought to target main cost driver, such as the discount rate (e.e.g, via the provision of low-carbon loans or credit guarantee vehicles). These policy proposals should then be audited and if endorsed financially supported by the international community (e.g., via the Green Climate Fund established under the Cancun agreement).

Overall, our findings support the call by Bazilian and colleagues (2010) for shifting the policy focus from mere (global) climate policy to (nationally designed) energy policy which integrates climate change mitigation as one core objective. International coordination of these policies could increase the efficiency and effectiveness of the incentives.

5.3 Suggestions for future research

Innovation scholars should aim at better instructions for policy makers (Dosi, 2010). While this thesis aims at this target by shedding light on the differences of technologies in different contexts over time as well as the role of different policy instruments aiming at technological change, a much better understanding of the role of policy for technological change is needed. Based on the findings of this dissertation, five fields of future research are proposed.

First, more research on the interaction of policy instruments is needed. We show that different instruments of the policy mix have very different effects (Papers 5 and 6). Several scholars have analysed the role interaction of different instruments on the macro level (for an overview see e.g., Fischer and Preonas, 2010). However, cost reductions of low-carbon technologies in different stages of the technology cycle depend on different forms of learning, i.e., learning based on R&D or learning based on production (Papers 2 and 3). Hence, for some technologies R&D support might be more important, for others demand-pull instruments. The interaction of instruments might therefore also depend on the technology characteristics. Instruments might also interact very differently for dissimilar groups of actors (paper 6). In sum, the understanding of the policy instruments' interaction and how this depends on the underlying learning mechanisms and heterogeneity of actors needs to be improved by future research with a micro-level focus.

Second, as "inventions hardly ever function in isolation" (Rosenberg, 1982, p. 56), complementary technologies are often necessary to enable the invention and almost always essential for large scale diffusion (Hughes, 1987). In order to support policy makers in designing effective policy mixes, single technologies should not be analysed separately but in a more systemic manner and by including their interactions. In particular, the role of storage and grid technologies as well as natural gas (which could be used as one backup technology for intermittent RET in the near- and medium-term[10]) as enabling technologies for the large scale diffusion of RET is under-researched. Innovation scholars should analyse these technologies in detail as their costs and performance might be essential for low-carbon technological change in the power sector.

Third, for explaining the link between corporate innovation activity changes on the micro- and technological change on the macro-level (which is not the explicit content of this thesis; compare the dashed arrow in Figure 2 in Section 2), a systemic perspective on the actors and their interactions is useful. Technological regimes, in which technologies co-evolve and of which these firms are

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[10] In fact, the steam engine was initially used as backup technology for intermittent hydro power (Fouquet, 2008).

members, have an important role in evolutionary transition mechanisms (van den Ende and Kemp, 1999). In order to govern such regimes, policy needs to be very well informed about the interaction of actors (Smith et al., 2005). Research on so-called sectoral and technological innovation systems (SIS and TIS) and their functions has increased our understanding of the role of such regimes (Bergek et al., 2008; Carlsson and Stankiewicz, 1991; Edquist et al., 2005; Hekkert and Negro, 2009; Hekkert et al., 2007; Malerba, 2002, 2005). In order to better grasp the role of technology differences and complementarities (see first and second point), a comparison of the innovation systems of different technologies and their functionalities is suggested. Based on such research, policy instruments that do justice to the differences of the structure and functionality of the TIS could be developed. Furthermore, analysing power generation technologies in very different contexts, e.g., when used in micro-grid or off-grid applications, can enhance the understanding of the role of actors and their interactions in the embedding contexts.

Fourth, two findings and associated policy recommendations of this thesis appear conflicting. On the one hand, the speed of technological change necessitates dynamic policy making as policy that lags behind technological progress might lead to an overcompensation of low-carbon technologies and thereby set wrong incentives (Papers 2 and 4). On the other hand, predictable regulation is essential in order to effectively incentivise firms to react to policy changes with R&D and diffusion activities. Future research should support policy makers by analysing how these two conflicting requirements can be integrated.

Fifth, transition scholars should increase their understanding of the political processes in order to provide more practical policy recommendations (Meadowcroft, 2011). One important aspect is the need to align economic and environmental objectives, which are usually advocated for by different political institutions (Alkemade et al., 2011; Bazilian et al., 2010). Future research is needed which considers different frames of these objectives. Another aspect is analysing the reverse influence to the one focused on in this study, i.e., that of actors on policy. However, it is not only actors who influence policy; Other institutions, e.g., standards, are also important for technological change (David and Rothwell, 1996). As the integration of large shares of intermittent RET into the existing power grids might lead to a new way of operating these (open assembled) systems, new standards might be needed (compare the historic excursus in Section 1). Analysing their role for the necessary low-carbon transition is thus of great interest. Another important aspect for future research in the political economy is the role of implementing new policies with potentially far-reaching consequences. The introduction of the EU ETS was dearly bought (Paper 5). Hence, an important question for future research should circle around the degree of leniency that is necessary in order to make new policy instruments politically feasible.

Let me end with a higher level perspective. In his seminal article, “Die Frage nach der Technik” (The Question Concerning Technology), Martin Heidegger (1954) argued that modern technology strongly differs from traditional technology[11]. For him, modern technology is a “challenging of nature”. He argues that the advent of modern technology made it possible to build in (“verbauen”) nature within technology and thereby make nature “something at our command”. Heidegger concludes that therefore the essence of modern technology involves a danger for mankind. Climate change certainly represents such danger stemming from the use of modern technology. However, for Heidegger, there is also a “saving power” which resides in modern technology. The key to unlocking this power is to start heeding the essence of technology by reflecting on technology and its development. Nevertheless, as “the essence of technology is nothing technical” the debate on its essence should take place in related but different arenas[12]. For me, his argument underpins the importance of sustainability oriented socio-economic studies on technology.

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[11] Interestingly his examples on modern technology mostly refer to electricity generation.

[12] In fact, Heidegger saw arts as one discipline that should address the need for understanding the essence of technology.

6. Overview of the Papers

All six papers are included in the Annex as published in or submitted to the respective journal. The submission status in Table 4 is as of September 30, 2011.

Table 4: Overview over the papers and their research questions

	Title	Authors	Journal	Status
1	Assessing the cost of PV and wind in six developing countries: Implications for post-Kyoto[13]	Schmidt, T.S., Born, R., Schneider, M.	Nature Climate Change	Under review
2	Shedding light on solar technologies – a techno-economic assessment and its policy implications	Peters, M., Schmidt, T.S., Wiederkehr, D., Schneider, M.	Energy Policy, 2011 39 (10): 6422-6439	Published
3	Japan’s post-Fukushima Challenge – Implications from the German Experience on Renewable Energy Policy	Huenteler, J., Schmidt, T.S., Kanie, N.	Energy Policy (viewpoint)	Under review
4	Composting projects under the CDM: Sustainable contribution to mitigate climate change	Rogger, C., Beaurain, F., Schmidt, T.S.	Waste Management, 2011 31(1): 138-146	Published
5	Climate policy’s impact on the rate and direction of corporate innovation activities – a survey of the European electricity sector[14]	Schmidt, T.S., Schneider, M., Rogge, K., Schuetz, M., Hoffmann, V.H.	Environmental Innovation and Societal Transitions	Under review
6	Decarbonising the power sector via technological change – differing contributions from heterogeneous firms[15]	Schmidt, T.S., Schneider, M., Hoffmann, V.H.,	Energy Policy	Under review

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[13] In earlier versions presented at:
  - Risø International Energy Conference 2011, Roskilde/Denmark, May 10-12, 2011
  - Zurich Carbon Market Association’s (CMA) “Workshop on NAMAs”, March 31, 2011
  - International workshop on low-carbon governance architecture: Technology innovation and transfer, Tokyo Institute of Technology, Tokyo/Japan, January 27, 2011

[14] In earlier versions presented at:
  - The 9th International Conference of the European Society for Ecological Economics, Istanbul/Turkey, June 14-17, 2011
  - International workshop on low-carbon governance architecture: Technology innovation and transfer, Tokyo Institute of Technology, Tokyo/Japan, January 27, 2011
  - The 13th Conference of the International Schumpeter Society, Aalborg/Denmark, June 21-24, 2010
  - Technical Change: History, Economics and Policy (Nickfest), Sussex/UK, March 29-30, 2010
  - United Nations International Climate Change Conference – UNFCCC COP 15, Copenhagen/Denmark, December 7-18, 2009

[15] In an earlier version presented at:
  - DIME Final Conference, Maastricht/The Netherlands, April 6-8, 2011

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Annex I

Paper 1

Assessing the costs of PV and Wind in six developing countries: Implications for post-Kyoto

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- Under review for Nature Climate Change -

Introductory Paragraph

The 2010 Cancun Agreement aims to limit global warming and therefore established a financial mechanism administered by the Green Climate Fund (GCF) to support developing countries in greenhouse gas (GHG) emission abatement. However, discussions regarding how to effectively utilise this support in a post-Kyoto climate policy regime continue. These discussions are predominantly underpinned by rather aggregate, strongly varying top-down estimates. To complement these numbers we provide a fine-grained yet replicable bottom-up approach comparing the abatement technologies PV and Wind in six developing countries. The results bear important implications for the post-Kyoto debate. First, they highlight the need for a decision on a "fair" baseline calculation methodology which incentivises baseline activities and thus reduces developing countries' financial support needs. Second, our study suggests that Nationally Appropriate Mitigation Actions (NAMAs) are more suited than a reformed Clean Development Mechanism (CDM) to foster the diffusion of different abatement technologies, whose costs can vary strongly across countries.

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Under the Kyoto Protocol, developing countries remain without GHG emission reduction obligations but are addressed by the CDM[1]. While important, the CDM failed in leveraging private investments (in 2010 an estimated $23bn[2]) in the magnitude needed[3]. As one vehicle to scale up finance, the Cancun Agreement establishes a financial mechanism aiming at "mobilizing jointly USD 100 billion per year by 2020 to address the [mitigation and adaptation] needs of developing countries"[4, p. 15]. However many issues remain unresolved, of which we address two.

First, a debate over how to determine different countries' financial needs for emission abatement[2,5], to be financed by developed countries, exists[6]. For instance, in the power sector, the biggest contributor to anthropogenic GHG emissions[7], renewable energy technologies (RET) have large abatement potential[8,9]. However, there is "a striking dearth in reliable peer-reviewed data on what it costs to generate renewable electricity and what determines those costs"[10]. Currently, the debate is mainly supported by top-down estimates on a very aggregate level. It is estimated, for example, that additional investments in RET of about €1.2tn from 2010 to 2030 (50% thereof in non-OECD countries)[11] and the coverage of their annual incremental costs at $27bn[12] are needed to reach the 450 ppm climate target. Furthermore, estimates vary strongly due to differences in assumptions and methodologies[2]. While such numbers are important for approximating total financial needs, more detailed data is needed to account for costs differing strongly across countries and technologies[13].

Second, which instruments are most effective for distributing financial resources in a post-Kyoto regime is heavily debated[14]. On the one hand, several major shortcomings of the CDM have been identified[3,15], spurring a discussion on CDM reforms such as differentiating technologies or countries and up-scaling via "Programs of Activities" (PoAs)[3]. On the other hand, NAMAs – "a set of policies and actions tailored to the circumstances of individual countries" – have received increased attention[14, p.32]. Proposed by the respective country but financed domestically and/or internationally, via the new financial mechanism or carbon markets[16]for example, NAMAs fuel the hopes of higher emission reductions because they are able to induce "long-term transformative processes" [14, p.32]. Fine-grained analyses of the costs and potential of abatement options could also support this debate[3].

Bottom-up studies currently available do not provide the aforementioned debates adequate support for two reasons. Either the technologies' costs in developing countries are discussed rather generically and do not yield insights into concrete country contexts[8,13] or they have a very narrow focus on a particular application (e.g., a project focus[17]), thus impeding comparative analyses of potentials and costs on a national or regional level.

We address this gap by analyzing the incremental costs of Wind and PV – two technologies with abundant natural potential – in six developing countries. More specifically, we apply a consistent methodology comprising the following steps (compare Supplementary Figure 1): (1) calculation of the levelised costs of electricity generation (LCOE) of the baseline power mix, (2) calculation of LCOE of

PV and Wind, (3) derivation of the incremental costs of both electricity generation and emission abatement, (4) analysis of the effects of fuel subsidies on these costs. We conclude with implications for the aforementioned debates on financing needs and instrument choice.

1 The costs and emission baseline of electricity generation in developing countries

For our study, we chose six countries reflecting differences in country size, development status and marginal baseline mixes (compare Figure 1 and Supplementary Note 1). With respect to the technology mix, the two largest countries, Brazil and India, are very heterogeneous and thus render an accurate analysis of the entire country impossible. We therefore focus on specific regions: In Brazil the north-eastern power grid region and in India, where power regulation is mainly enacted on the state level[18], the state of Karnataka (hereafter $\text{Brazil}_{\text{NE}}$ and India_{KA}). We calculate the LCOE (compare Supplementary Equation 1) and emissions for each of the six countries' electricity generation baseline mix.

While the emission baseline calculation is highly standardised and well documented in the current CDM regime, the financial baseline calculation differs from project to project (and is not even considered for all projects)[19]. In contrast, we consistently apply one methodology. First, due to rapidly growing energy demands in all six countries[11], we do not assume that new RET installations replace existing capacity and thus focus on the marginal baseline. Hence, we follow the CDM "build margin" methodology to obtain the marginal baseline technology mix (compare Supplementary Table 1).

Second, we calculate the LCOE of that marginal baseline mix in a way that deviates from current CDM methodologies in two respects. Instead of using the actual baseline, i.e., including fuel subsidies and the new installation of obsolete equipment, we decided to use global (i.e., unsubsidised[20]) fuel prices (see supplementary Figure 2) and state of the art technology (Supplementary Table 2) in our model. This approach has the advantage of not favouring countries employing practices obstructive to climate change mitigation. Countries are neither rewarded for fuel subsidies (which lower the cost baseline and thus result in higher incremental costs) nor – due to less pressure on improving efficiency – for the often related installation of outdated technology that raises the emissions of the marginal baseline and thus increase the rewards for abatement. These assumptions allow the comparison of countries' baselines on a level playing field. Furthermore, we consistently apply country specific discount rates (see Supplementary Table 3) – reflecting varying political and legal risks[21] – in order to capture the views of private investors, who will need to finance most of the investments.

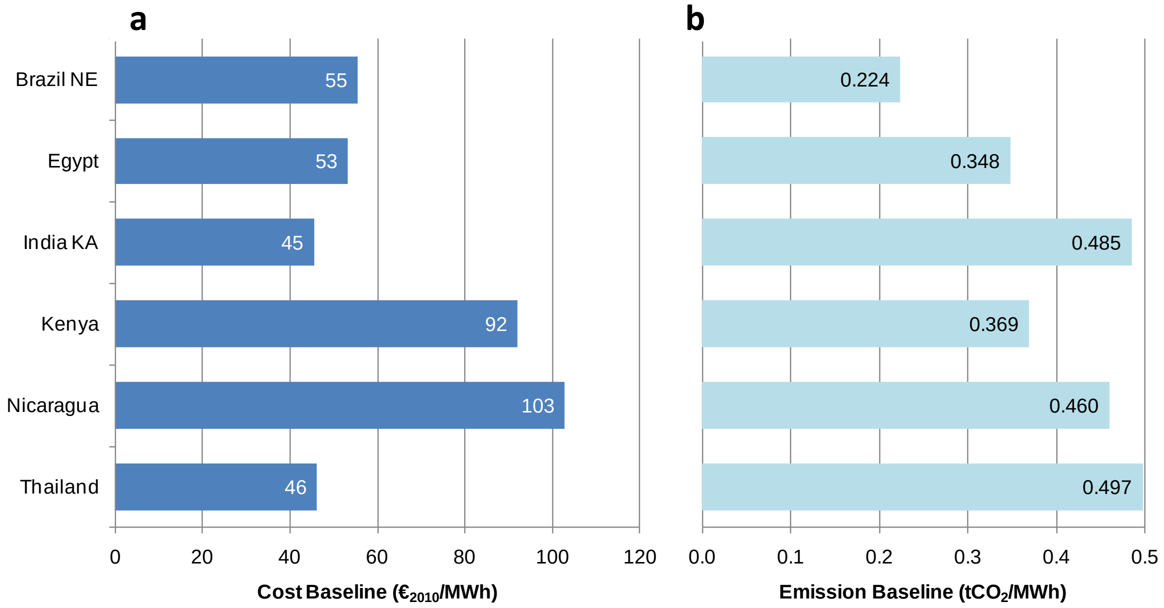

Figure 1: The 2010 marginal baseline electricity generation mix. The bars depict the marginal cost baseline, i.e., the LCOE of the power generation mix to be built without policy mechanisms in place **(a)** and the corresponding emissions per MWh of electricity produced **(b)**.

With LCOE differences of up to a factor of 2.3 (see Figure 1a) our results highlight the large heterogeneity between the countries' marginal baselines. Kenya and Nicaragua particularly stand out because their marginal baseline mix is dominated by oil fired plants, a very costly fuel if unsubsidised. With regards to emissions (see Figure 1b), we observe differences up to a factor of 2.2. Marginal capacity additions in Brazil$_{NE}$ exhibit a low baseline due to the dominance of hydro and gas in the energy mix, while India$_{KA}$ and Thailand have a high baseline due to a strong reliance on hard coal plants. The marginal emission and cost baselines are not correlated, as for instance rather inexpensive technologies can have zero (e.g., hydro) or very high (e.g., hard coal) direct emissions.

2 The costs of renewable electricity generation

In order to calculate the LCOE of RET in a manner that allows a "fair" country-technology comparison, we set a 10% target share of national electricity production for each technology. This share exceeds a minimum market size necessary to build a local supportive business context that benefits from interactive learning between the relevant actors[22] while at the same time not causing major grid stability issues[23]. In order to represent private investor behaviour, we applied a search algorithm (compare Supplementary Note 2) so as to identify the most attractive sites for the instalment of RET in each country and again used country specific discount rates (see Supplementary Table 3). Based on accurate data (see Supplementary Tables 4 to 6) we calculate the LCOE of RET, which can be used as an estimator for the necessary height of a feed-in tariff (FIT), a potential NAMA instrument with a proven track record of effectively leveraging private investments[16]. Finally, we performed a sensitivity analysis on grid connection costs (see Supplementary Table 7) as electricity grids are an essential pre-condition for the large scale diffusion of RET[24] (non-grid connected small scale RET exhibit very different economics and are not considered in this study).

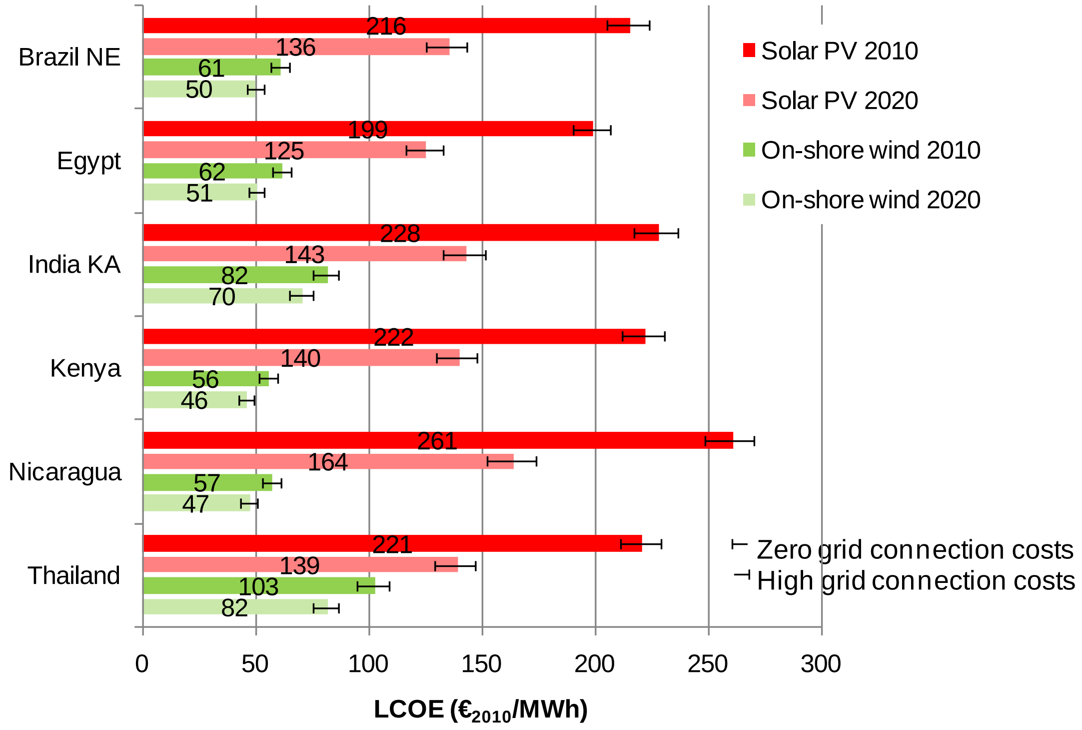

Figure 2: The LCOE of solar PV and Wind in 2010 and 2020. The bars depict the LCOE (€$_{2010}$) of solar PV (red) and wind (green) at the 10% target share threshold, assuming average grid connection costs. The dark coloured bars represent the LCOE of state of the art technology (2010), the light coloured ones those of technology installed in 2020. The left end of the black stripes represents the LCOE without grid connection costs, the right end those with very high grid-connection costs.

Our results (see Figure 2) show that PV has generally much higher LCOE than wind in 2010 (between 2.2 to 4.5 times), mainly due to a lower amount of electricity generated per invested Euro. Though large cost reductions within the next ten years are expected, the LCOE of PV in 2020 remain much higher than those of wind (factor 1.7 to 3.4). Therefore, large-scale PV is rather a long-term option for emission abatement in developing countries. The relatively low cost reductions of wind make the 2010 numbers a good estimator for near term incremental costs against the marginal baseline calculated above. For each technology we also observe differences across countries (up to a factor of 1.3 for PV and 1.8 for wind). In relative terms, these differences barely change over time. They are predominantly driven by varying solar and wind resources as well as the discount rate, whereas the influence of the grid connection costs is relatively low.

3 The incremental costs of electricity generation and emission abatement

After having shown the large cost-variation of both the baseline and the RET we now turn to comparing their costs in two dimensions. First, we calculate the incremental costs of RET per MWh by subtracting the baseline LCOE from the RET LCOE. Second, we calculate the incremental costs per avoided ton of CO_2, synonymous with the nominal abatement costs or the carbon price needed in order to cover the incremental costs.

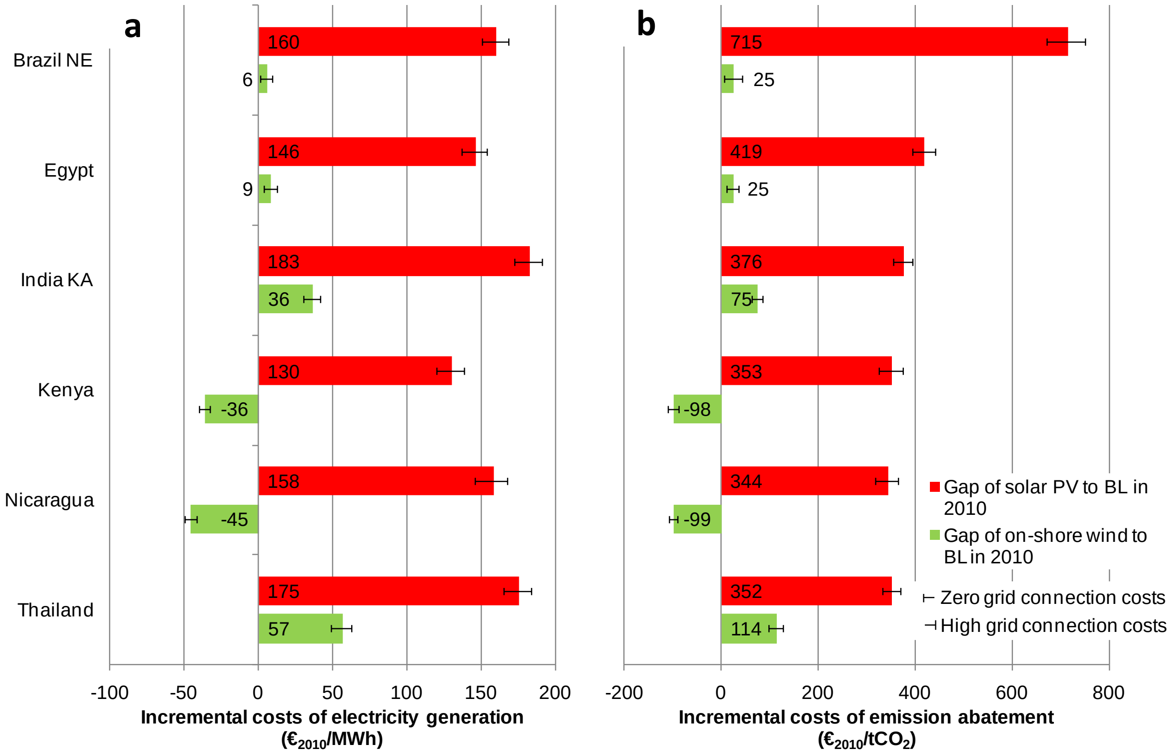

Figure 3: The incremental costs of electricity generation (a) and emission abatement (b). The red bars depict the incremental costs of solar PV, the green bars those of wind. Again, the influence of the grid-connection costs is depicted by the black stripes.

The incremental costs of electricity generation (Figure 3a) of PV are very high in all countries due to its hitherto high LCOE (compare Figure 2). As an aside, the incremental costs of PV can be much smaller (or even negative) in off-grid applications, where the LCOE of the baseline technology (e.g., a diesel generator) are often very high[25,26]. Regarding wind, three groups of countries can be identified. In India_{KA} and Thailand the incremental costs are very high because of the low baseline LCOE and the relatively high wind LCOE. The incremental costs in Brazil_{NE} and Egypt are close to zero due to the higher baseline LCOE and significantly lower wind LCOE. In Kenya and Nicaragua, strikingly, the incremental costs of wind are highly negative as the high baseline LCOE by far exceed the wind LCOE. The large differences between PV and wind in all countries, as well as the variation of wind across countries, highlight that the incremental costs are determined by the specific technology-country combination and not by either technology or country.

The abatement costs (Figure 3b) vary in a similar way. For PV they are very high in all countries, with Brazil_{NE} being an upward outlier due to its low baseline emissions. Regarding wind, the same three groups of countries emerge. While the emission-specific incremental costs in Egypt and Brazil_{NE} are roughly twice the 2010 average price of CDM credits on the spot market[27], those in India_{KA} and

Thailand are significantly higher. Kenya and Nicaragua show negative abatement costs at almost 100€ per ton of CO_2. At this point, one might ask why wind is not then strongly represented in the baseline mix of these countries. Here the role of fuel subsidies becomes important. While we excluded them from our baseline calculation, their role is examined in more detail in section 4.

4 The impact of fuel subsidies on the incremental costs of RET

So far, we have calculated the baseline LCOE assuming state of the art technology and no fuel subsidies. While the impact of the technology choice is relatively low (see supplementary Note 3), fuel subsidies, which occur in many forms[28], can have major effects. In order to quantify these effects, we compare the unsubsidized baseline LCOE with the subsidized ones. We then calculate the incremental costs of RET against the subsidized baselines and compare them with the LCOE calculated above (in section 3). While we found anecdotal evidence for large fuel subsidies in the power sectors of Kenya and Nicaragua and numbers on the overall power sector subsidies in India and Thailand (see supplementary Note 4), our analysis is limited to $\text{Brazil}_{\text{NE}}$ and Egypt. Only here was fuel-specific subsidy data available, showing that power generators in both countries purchase natural gas from state-owned providers at about 50% of the global price (compare Supplementary Figure 2).

Our results (Figure 4) show how fuel subsidies can “artificially” distort the competitiveness of RET. This effect is most pronounced for those RET whose LCOE are relatively close to the unsubsidized baseline. While the fuel subsidies currently present in $\text{Brazil}_{\text{NE}}$ and Egypt reduce the baseline LCOE by 13% and 21% respectively, their effect on the incremental costs of wind is much higher. In fact, the incremental costs are more than doubled by the subsidies. Due to the high LCOE of PV we do not observe such strong relative effects of fuel subsidies on this technology.

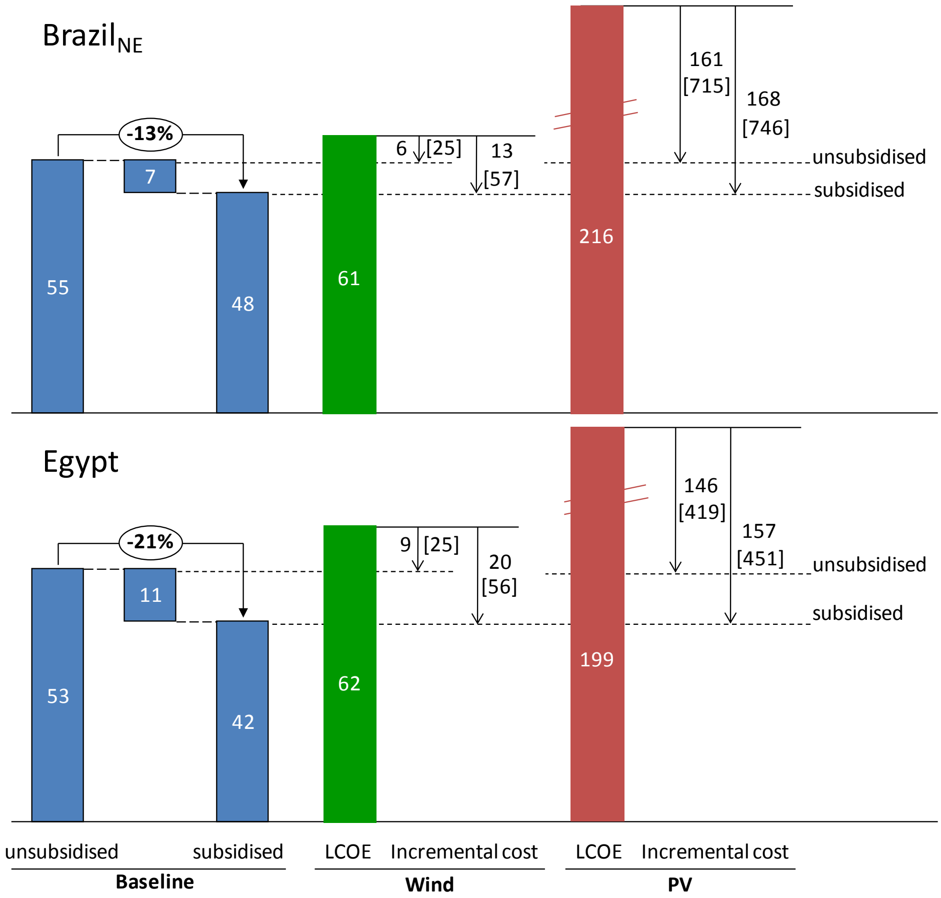

Figure 4: **The effect of fuel subsidies on the incremental costs of RET.** We show the unsubsidized and subsidized baseline LCOE (blue) and compare them with the LCOE of wind (green) and PV (red). The resulting energy-specific incremental costs (in €$_{2010}$/MWh) are denoted next to the arrows. The numbers in brackets represent the respective CO_2-specific incremental costs (in €$_{2010}$/tCO_2).

5 Implications for future climate policy and research

While our study just sheds light on a small proportion of emission abatement options in developing countries, it bears implications for the post-Kyoto debate. Below, we discuss the two results with the most important implications for the instrument debate and the financial-needs debate.

First, the large variation observed in the abatement costs support the proposals to reform the CDM via differentiation in the instrument debate. However the finding that the incremental costs strongly differ between specific country-technology combinations suggests that differentiation should be done on the basis of such country-technology combinations rather than by separating technology and country, as is currently being debated[3]. A centralised redistribution of credits on a country-technology specific basis by the UNFCCC is likely to increase the complexity of a reformed CDM and thereby raise its administrative costs and time requirements, for which the current CDM is already criticised[29]. By contrast, nationally designed NAMAs can address country-technology combinations well, e.g., via technology specific feed-in tariffs on a national (or even regional) level, without requiring excessive expenditure in terms of administrative costs and time. However, the efficiency of NAMAs depends much more on the institutional capacity and size of the respective developing country than the CDM with its transparent governance structures[30,31]. For very small countries and those with relatively low institutional capacity, a reformed CDM might therefore be a more suitable instrument. In this context, Programs of Activities (PoAs) could represent a transitional solution as they allow for up-scaling the small-sized CDM and can be designed in a way that comes close to a NAMA but do not depend as much on the host country's institutional capacity[15,30].

For the financial-needs debate, the country-technology-specificity of incremental costs observed highlights the need for very fine-grained (bottom-up) yet replicable assessments on the technology and country level. Approaches like the one presented in this paper are useful as they allow a country-technology comparison and can be adjusted, e.g., by choosing different target shares, and extended, e.g., to more technologies. In order to reduce the incremental costs of abatement technologies to a minimum, several instruments, such as FIT, low-interest loans or guarantee vehicles and investment subsidies, should be taken into account to calculate an ideal instrument mix for each country-technology combination. In order to arrive at a "fair" distribution of the financial mechanism funds, assessments, administered by the GCF for example, of all countries and technology options would be ideal (Supplementary Table 8 shows the cost of reaching the 10% target share and the potential for leveraging private investments for the two technologies and six countries analysed).

The second important finding, the role of subsidies, reveals that tackling the baseline is a key issue for paving the way for large scale investments into abatement technologies in developing countries. Regarding the instrument debate, the CDM currently provides no incentive for addressing the baseline. It is questionable whether CDM reforms such as the introduction of sectoral baselines provide sufficient incentives to address the issue of subsidy reform. By contrast, through their more encompassing scope NAMAs can combine the support of abatement technologies with instruments addressing the baseline. Our results suggest that they could thereby leverage private investments into abatement technologies at much lower incremental costs from a global perspective.

Taking up these issues, the debate on determining financial needs should focus on the question of what constitutes a "fair" baseline. A standardised methodology, as exists for the emission baseline under the CDM, also needs to be set for the financial baseline. In this study (see section 1 for details), we suggested that a starting point for this debate is the exclusion of fuel subsidies and the installation of outdated equipment so as to avoid distortions. In theory, this implies that subsidy removal should be financed (mainly) by the host country and only the incremental costs of abatement technologies against a "fair" baseline should be supported or entirely financed internationally. However, in order to address possible domestic political resistance[28], some sort of support from international institutions might be needed. In any case, our findings show that there is an urgent need for better data on subsidies. Possibly, further international support to countries might make the transparent reporting of such data a first condition.

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Supplementary information

NOTES

Supplementary Note 1: Selection of countries

The six countries under study were chosen in order to include 2 countries per continent that hosts developing countries (Africa, America, Asia) that have different sizes (from Nicaragua to India) and development states. Kenya, ranked 128 in the UNDP's Human Development Index 2010[1], and Brazil, ranked 73, define the lower and upper bound in our sample. With the selection we also aimed to include countries with very different baseline technology mixes (compare supplementary Table S2). Finally, the availability of data was an important selection criterion.

Supplementary Note 2: Determining the full load hours of PV and on-shore wind.

The full load hours represent the RE resources in a specific location. A full load hour is an hour at which a plant produces energy at full capacity. For PV, the full load hours depend on the solar irradiation, for wind turbines on the wind speed and occurrence. We assume that investors in RET search for the locations with the best solar/wind resources. Investors will erect PV/wind plants at sites with the best resources (i=1) until these are exhausted. They will then move to the second best (i=2), third best (i=3) sites etc., until the 10% target share of electricity production is reached. The following formula depicts this search algorithm:

$$while\ El_{10\%} \geq El_{RET} \quad : \quad El_{RET} = \sum_i El_i$$

With:

$El_{10\%}$: $10\%\ target\ share\ [MWh]$

El_{RET}: $Electricity\ generated\ by\ RET\ [MWh]$

El_i: $Potential\ electricity\ generation\ at\ sites\ i\ [MWh]$

The electricity generated at sites *i* is then calculated using the following formula:

$$El_i = \eta_{system} * flh_i * CD_i * A_i$$

With:

η_{system}: $net\ efficincy\ of\ the\ installed\ RET\ plant\ (system\ level)$

flh_i: $full\ load\ hours\ at\ the\ sites\ i$ *(see below)*

CD_i: $Capacity\ density\ at\ sites\ i$ *(see below)*

A_i: $surface\ area\ of\ sites\ i$

For PV the full load hours are derived from NREL solar irradiance data[2,3,4] with a 40km x 40km resolution via an asymptote[5, Figure 6.31] and compares well to a very recent peer-reviewed study[6]. The results can be found in supplementary table XY.

For wind, the full load hours depend on the hub-height, wind speed and occurrence. The wind data used was taken from the "FirstLook" database[7] of 3Tier. In our model we use hub heights of 80m in 2010 and 110m in 2020.

The full-load hours are calculated based on the following equations[5, p. 55,8, p. 17]:

$$flh_{Windi} = v_{heighti} * 626.5 - 1901$$

With

$$v_{heighti} = \left(v_{refHi} * \left(\frac{height_i}{ref_H} \right)^{C_{Hell}} \right) \quad \text{(Hellmann equation)}$$

$v_{refHi} = wind\ speed\ at\ reference\ height\ of\ resource\ data\ map$

$ref_H = reference\ height$

$height = target\ height$

$C_{Hell} = Hellman\ coefficient = 0.3$

The capacity density represents the amount of capacity that can be built on one area unit. It depends on the technology as well as on the surface of the area. The following equation is used for PV:

$$CD_{PV} = \left(\left(\eta_{PV} * \left(\frac{1}{\cos \alpha} \right)^{-1} \right) * C_{shadow} \right) * C_{surfacePV}$$

With

$\alpha = inclination\ angle = 20°$

$C_{shadow} = shadowing\ coefficient = 0.35$

$C_{surfacePV} = surface\ coefficient\ (area\ occupiable\ by\ PV\ modules) = 0.5$

All three values are chosen conservatively.

For wind the following formula is used [5,9]:

$$CD_{Wind} = \left(\frac{Capacity}{A_{turbine}} * 10^6 \right) * C_{surfaceWInd}$$

With:

$$A_{turbine} = \sqrt{\frac{3}{4}} * (C_A * D_{rotor})^2$$

C_A: $Area\ coefficient = 10$

D_{rotor}: $Rotor\ diameter\ of\ turbine$

$C_{surfaceWind}$: $Surface\ coefficient\ (possible\ land\ occupation) = 0.25$

For wind all values are chosen conservatively. The results of the calculations for PV and wind per country can be found in supplementary tables XX and YY.

Supplementary Note 3: Comparison of subcritical and supercritical pulverized coal power plant generation costs

Assuming an efficiency rise of supercritical over subcritical technology of 5.1% and investment costs which are 3.1% higher[10], supercritical plants have LCOE which are 3.5% below those of subcritical plants in India and 3.4% in Thailand.

Supplementary Note 4: Fuel subsidies in India, Thailand, Kenya and Nicaragua and

The "2010 World Energy Outlook" [11, p. 575] estimates the economic value of fossil fuel subsidies based on the price-gap method by comparing local prices with international market prices correcting for transport and distribution.

For India the electricity subsidies for fossil fuel inputs for power generation are an estimated $5bn p.a. In Thailand, they are about $1.5bn p.a. Yet, only numbers on the entire sector are available making it impossible to calculate the price distortions for the marginal baseline. As the price control mechanisms in Kenya or the preferential oil imports in Nicaragua cannot be captured by the price-gap method, Kenya and Nicaragua are not listed by the IEA.

According to the 2009 report "Government Response to Oil Price Volatility"[12] the Energy Regulatory Commission of Kenya circulated regulation drafts for setting maximum retail prices in 2008. In the same period the president appealed to fuel suppliers to lower prices. When it showed that these requests had little impact the Kenyan Energy Ministry stopped buying fuels from other suppliers than the National Oil Corporation of Kenya and furthermore launched a campaign to force fuel suppliers to lower prices. In addition, the Energy Minister said that he was not satisfied with the oil companies' response and therefore considers the reintroduction of price control. In January 2009 the government increased the possibility of effective indirect price control via the introduction of further measures. These activities influence retail as well as wholesale prices.

In Nicaragua the following anecdotal evidence points to major fuel price distortions. In order to support Nicaraguan President José Daniel Ortega Saavedra, Hugo Chavez provided oil imports at premium conditions [13] and thus making conventional plants more attractive.

TABLES

Supplementary Table 1: Country specific technology mix* of the baseline[11,12,13,14,15,16]

	Brazil NE	Egypt	India KA	Kenya	Nicaragua	Thailand
Natural gas combined cycle	64.3%	100.0%	17.2%			60.4%
Super critical pulverised coal			58.7%			39.6%
Large Hydro	35.7%		24.1%			
Liquid fuel combined cycle				20.0%	100.00%	
Oil Steam turbine				48.8%		
Geothermal				31.2%		

*In order to select the marginal baseline mix we used the “build margin“ methodology (i.e. the most likely plant mix to be built in future) of the UNFCCC[17]. Other relevant studies also argue that in the power sector the marginal baseline is most appropriate[18]. Plants with a likelihood of being built of 10% or less are not considered. Nuclear plants (relevant in India$_{KA}$, only) were excluded because of the very unclear situation post-Fukushima.

Supplementary Table 2: Techno-economic assumptions of the baseline technologies [19,20,21]

		Investment cost* [€/MW]	O&M cost** [€/MW]	Full load hours [h]	Life-span [yrs]	Net system efficiency [ ]	Emission factor [tCO_2/ GWh]
Natural gas combined cycle	2010	700'000	27'000	7008	25	58%	348.2
Super critical pulverised coal	2010	1'400'000	66'000	7008	40	47%	724.5
Large Hydro	2010	1'500'000	44'000	4380	50	1***	0.0
Liquid fuel combined cycle	2010	700'000	27'000	7008	25	58%	568.6
Oil Steam turbine	2010	750'000	37'000	7008	30	49%	459.9
Geothermal	2010	1'600'000	76'106	7884	30	1***	0.0

* overnight, without grid connection cost

** fixed annual cost

*** for large hydro and geothermal plants, efficiency losses are included in the capacity

Supplementary Table 3: Country-specific nominal discount rates used for the baseline and RET LCOE (following the UNFCCC proposal[22] for the power sector)

	Nominal discount rate*
Brazil NE	13.85 %
Egypt	14.10 %
India KA	13.85 %
Kenya	15.35 %
Nicaragua	17.60 %
Thailand	13.30 %

* in real nominal terms, with an assumed €-inflation rate of 2.13% [23]

Supplementary Table 4: Techno-economic assumptions of PV and on-shore wind[6,8,24,25]

		PV, crystalline**		On-shore wind	
		2010	2020	2010	2020
Investment cost* [€/MW]		2'486'949	1'564'058	1'183'000	1'097'460
Annual O&M cost [€/MW]	at start of operation	37'304	23'461	1'069	1'069
	annual increase	0	0	3'952	3'952
Lifespan [a]		25	25	20	20
Net system efficiency***		11.3% (14.3%)	17.6% (22.0%)	90.2%	90.2%
Turbine capacity [MW]		-	-	2	5
Hub height [m]		-	-	80	110
Rotor diameter [m]		-	-	80	130

* overnight, without grid connection cost

** yearly capacity degradation rate of 0.0035

***For PV: module efficiencies given in brackets; for wind, this only refers to operational losses

Supplementary Table 5: Country-specific data on the electricity production and solar potential in 2010 and 2020[16,26,27]. The bold full load hour figures* are applied in the LCOE calculation.

	10% objective $El_{10\%}$ [GWh]	Site quality	Daily solar irradiation SIR [kWh/m^2]	**Full load hours flh_i**	Area A_i [km^2]	Potential electricity generation El_i, 2010 [GWh]	Potential electricity generation El_i, 2020 [GWh]
Brazil NE	4'225	Best	6.25	**1907**	200'000	7'175'226'069	11'038'809'337
Egypt	13'104	Best	7.25	**2091**	57'600	2'266'343'542	3'486'682'372
India KA	2'988	Best	5.75	**1803**	172'000	5'835'381'930	8'977'510'661
Kenya	706	Best	6.75	**2003**	132'800	5'003'307'255	7'697'395'777
Nicaragua	336	Best	6.25	**1907**	1'600	57'401'809	88'310'475
Thailand	14'740	Best	5.75	**1803**	489'600	16'610'482'517	25'554'588'487

*The 10% target share is always reached taking into account the sites with the highest solar resource only.

Supplementary Table 6: Country-specific data on the electricity production and wind potential in 2010 and 2020.[16,26,27] The bold full load hour figures* are applied in the LCOE calculation**.**

		10% objective $El_{10\%}$ [GWh]	Site quality	Annual average wind speed [m/s]	**Full load hour flh_i**	Area A_i [km^2]	Potential electricity generation El_i [GWh]
Brazil NE	2010	4'102	Best	9.0	**3738**	2'000	6'080
			2nd best	8.5	3424	12'000	33'422
	2020	4'102	Best	9.9	**4303**	2'000	6'627
			2nd best	9.4	3958	12'000	36'575
Egypt	2010	12'173	Best	9.5	4051	1'000	3'295
			2nd best	9.0	**3738**	3'438	10'450
	2020	12'173	Best	10.5	4648	1'000	3'579
			2nd best	9.9	**4303**	3'438	11'390
India KA	2010	2'988	Best	7.5	**2798**	2'000	4'551
			2nd best	7.0	2485	20'000	40'416
	2020	2'988	Best	7.9	**3062**	3'000	7'074
			2nd best	7.4	2717	25'000	52'312
Kenya	2010	706	Best	10.0	**4364**	2'500	8'874
			2nd best	9.5	4051	15'000	49'421
	2020	706	Best	11.0	**4992**	2'500	9'610
			2nd best	10.5	4648	15'000	53'681
Nicaragua	2010	336	Best	10.5	**4677**	100	380
			2nd best	9.5	4051	6'000	19'768
	2020	336	Best	11.6	**5337**	100	411
			2nd best	10.5	4648	6'000	21'472
Thailand	2010	14'743	Best	7.0	2485	4'000	8'083
			2nd best	6.5	**2171**	12'000	21'192
	2020	14'743	Best	7.7	2924	4'000	9'007
			2nd best	7.2	**2580**	12'000	23'836

*The 10% target share is reached taking into account the sites with the highest and (in some countries) second highest solar resource.

Supplementary Table 7: Assumptions on grid connection costs (the same capacity-specific costs for both technologies are assumed) [8,24]

	Average cost	High cost
Grid connection cost [€/MW]	117'000	208'000

Supplementary Table 8: Total cost and investments for achieving the 10% target share and leverage factor of private investments

	Annual total incremental Costs [m€$_{2010}$]		Annual emission abatements per technology [MtCO$_2$]	Initial investments [m€$_{2010}$]		Leverage factor**	
	PV (in% of GCF*)	Wind (in% of GCF*)		PV	Wind	PV	Wind
Brazil NE	676.4 (1.83%)	23.4 (0.06%)	0.95	5'098.3	1'298.5	1.09	8.30
Egypt	1'913.1 (5.17%)	104.7 (0.28%)	4.56	13'793.8	3'852.9	1.06	5.59
India KA	545.3 (1.47%)	108.4 (0.29%)	1.45	3'926.3	1'263.3	1.04	1.74
Kenya	91.9 (0.25%)	-25.5 (-0.07%)	0.26	834.9	191.2	1.44	-
Nicaragua	53.1 (0.14%)	-15.3 (-0.04%)	0.15	417.7	85.0	1.41	-
Thailand	2'577.8 (6.96%)	833.2 (2.25%)	7.33	19'374.3	8'032.3	1.05	1.40

*This refer to 50% of the annual bn100$, as the other 50% are to be used for mitigation. A $/€ conversion rate of 1.35 is assumed.

** The leverage factor quantifies how much investment is leveraged by the total discounted direct financial support covering the incremental costs over the lifetime (e.g. via a feed-in tariff).

EQUATION

Supplementary Equation 1: Levelised Costs of Electricity generation (LCOE)[6,28]

$$LCOE = \frac{\sum_{t=1}^{n} \frac{Expenditures_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{Electricity\ generated_t}{(1+i)^t}} \qquad \left[\frac{€}{MWh}\right]$$

With:

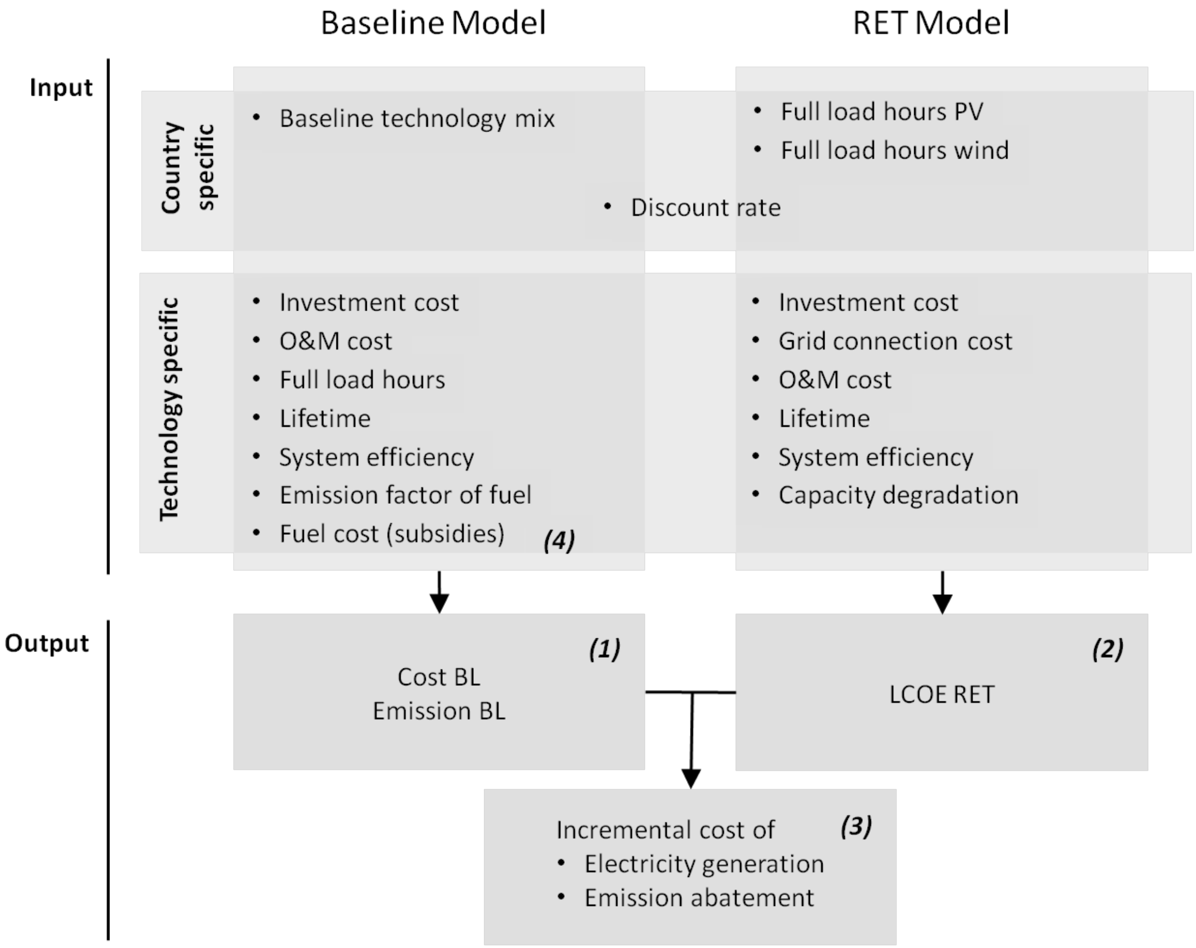
n: $lifetime$

t: $year$

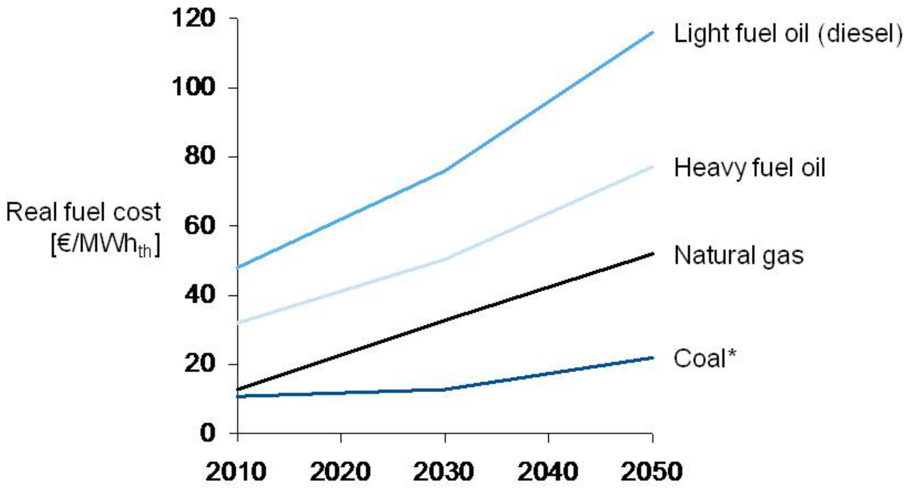
i: $Discount\ rate$

"The LCOE equation allows alternative technologies to be compared when different scales of operation, investment or operating time periods exist."[28, p. 421]

FIGURES



Supplementary Figure 1: Input and output variables of the Baseline (BL) and renewable energy technology (RET) model.



*FOB (free on board) prices. Country-specific freight cost for India are 1.47 €/MWh and 0.81 €/MWh for Thailand.

Supplementary Figure 2: Fuel cost assumptions of the baseline technologies. The costs at the start of the period are based on 2010 world market prices [29,30,31,32]. The trend is derived from a 2010 IEA baseline scenario[33]. For coal (relevant in India and Thailand) we assumed Indonesian imported coal [34] and added shipping costs[35] in the height of 1.43€/MWhth (India) and 0.72€/MWhth (Thailand) accounting for shipping distances of 2790nmi (India) and 1750nmi (Thailand). Fuel subsidies in Egypt and Brazil refer to natural gas and reduce its starting value to 50% of the assumed world market prices[36,37].

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Annex I

Paper 2

Shedding light on solar technologies – a techno-economic assessment and its policy implications

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- Published in Energy Policy (2011) 39 (10): 6422-6439 -
doi:10.1016/j.enpol.2011.07.045

Abstract

Solar power technologies will have to become a major pillar in the world's future energy system to combat climate change and resource depletion. However, it is unclear which solar technology is and will prove most viable. Therefore, a comprehensive comparative assessment of solar technologies along the key quantitative and qualitative competitiveness criteria is needed. Based on a literature review and detailed techno-economic modelling for 2010 and 2020 in five locations, we provide such an assessment for the three currently leading large-scale solar technologies. We show that today these technologies cannot yet compete with conventional forms of power generation but approach competitiveness around 2020 in favourable locations. Furthermore, from a global perspective we find that none of the solar technologies emerges as a clear winner and that cost of storing energy differs by technology and can change the order of competitiveness in some instances. Importantly, the competitiveness of the different technologies varies considerably across locations due to differences in, e.g., solar resource and discount rates. Based on this analysis, we discuss policy implications with regard to fostering the diffusion of solar technologies while increasing the efficiency of policy support through an adequate geographical allocation of solar technologies.

Keywords: photovoltaics (PV); concentrating solar power (CSP); technology policy

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1 Introduction

Society is facing serious problems such as climate change, resource depletion, and pollution. To meet these challenges a "technology revolution" (Galiana and Green, 2009) in the field of clean energy technologies is required in order to decouple economic growth from adverse environmental impacts. Solar power has the potential to become a protagonist in this “revolution”. According to forecasts of the International Energy Agency, solar technology could contribute 20% to global electricity generation in 2050 (IEA, 2010a). However, in 2010 the share of solar power has been well below 0.5% as the cost of solar technologies cannot yet compete with other forms of electricity generation. Significant innovation in solar power technologies are a prerequisite to unlocking the enormous potential of solar energy. A wide set of solar technologies is available in the field of photovoltaics (PV) and concentrating solar power (CSP) with differing performance characteristics.

Which technology is and will prove most viable in our electricity systems is heavily contested among scholars and industry experts (Fthenakis et al., 2009; PricewaterhouseCoopers, 2010). While the competitiveness of solar power generation differs by technology, time and location the extant literature lacks a holistic assessment of solar power based on these three dimensions. Integrating existing studies into one overall picture is not possible since they rely on a variety of methods and mostly inconsistent assumptions. Hence, there is a clear need to holistically and accurately assess key solar technologies on a common basis to guide users, investors, technology providers and policymakers in terms of investment and policy funding. In this paper we concentrate on recommendations for future policymaking as policy is likely to be the single most important lever to lead solar power towards competitiveness.

In order to provide a sound basis for our policy discussion (see section 6), this paper, therefore, focuses on the following research question: What is the competitiveness of leading solar technologies depending on time and location? Building on Tushman and Rosenkopf (1992), we assess solar technologies based on their key merit dimensions. While the levelized cost of generating and storing electricity (LCOE) is undisputedly the most important dimension of merit, qualitative aspects of solar technologies also impact their overall competitiveness. Therefore, we will focus more specifically on the following four sub research questions:

1) In 2010, how do PV and CSP technologies compare in terms of LCOE?

2) In 2020, how will PV and CSP technologies compare in terms of LCOE?

3) How do 2010 and 2020 LCOE of PV and CSP technologies change depending on local financing and weather conditions in present and future leading solar markets?

4) How do PV and CSP technologies compare along qualitative merit dimensions?

Methodologically, we construct a LCOE model, which is capable of quantifying the generation as well as the storage cost of PV and CSP electricity. To assure accuracy we choose a high degree of granularity in the input data. For projections we use a combination of bottom-up and top-down estimates (Neij, 2008). The qualitative evaluation of the remaining merit dimensions is conducted based on an extensive literature review and expert interviews.

This paper is structured as follows: In the subsequent section, we provide a short overview of solar technologies and markets. In section 3 the existing literature on techno-economic assessments of solar power technologies is reviewed. We describe the method and assumptions used in section 4. Based on the results, presented in section 5, we derive policy recommendations in section 6 before concluding in section 7.

2 An overview of solar technologies and markets

Solar power technologies can be divided into two main classes: photovoltaics (PV) and concentrating solar power (CSP). PV exploits the photovoltaic effect exhibited by semiconductors and thus directly converts solar irradiation into electricity. CSP systems use mirrors to focus sunlight onto a receiver in which a fluid (e.g., thermo oil or molten salt) is heated up to several hundred degrees Celsius. In a heat engine (e.g., a steam turbine) this thermal energy is then converted into electricity (Jacobson, 2009).

2.1 Photovoltaics

Since the patenting of the first solar cell in 1954 two principal types of PV technologies have emerged: wafer based crystalline silicon (c-Si) and thin film. While the former typically had market shares of 80%-90% in previous years, recently thin film technologies have been gaining ground. Even though the efficiencies of thin film modules are poorer, their cost per watt is lower due to less material usage (Bagnall and Boreland, 2008). In particular, cadmium telluride (CdTe) based modules have been successful lately due to their low cost position. Their market share increased from 1% in 2005 to 9% in 2009 (Photon, 2010). Other commercial thin film technologies such as copper indium gallium selenide (CIGS) and thin film silicon also increased their market shares in recent years. Dye sensitized (Graetzel, 2001) and organic solar cells (Brabec and Sariciftci, 2001) have developed quickly. However, these technologies are still in a pre-commercial phase (Photon, 2010). In addition, in the coming decades, so called third generation photovoltaics have the potential to lower the levelized cost of electricity by combining thin film approaches with high efficiency concepts (Green, 2006).

Although annual PV capacity additions have grown, on average, with more than 40% since 2000 (EPIA, 2010a), it is still at a very low level compared to globally installed power plant capacity (Figure 1). Driven by an attractive feed-in tariff scheme effective since 2000, Germany has gained a 42% share in installed PV capacity while only accounting for 3% of globally installed power plant capacity (Figure 1). Following the German example, other European countries have also introduced PV feed-in tariffs incentivizing capacity installations. In the past, PV policy support was rather limited outside of Europe resulting in a low non-European share of the world market. However, PV policy support is currently expanding globally and this will lead to an increasing share of non-European PV markets – particularly in China and the US (EPIA 2010).

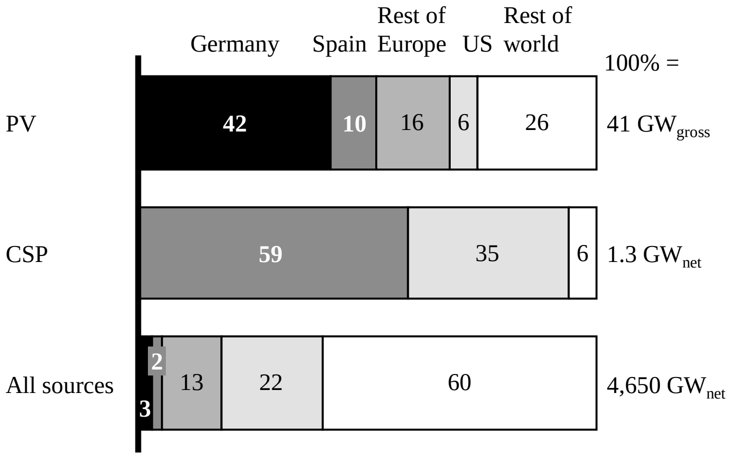


Fig. 1. Share of globally installed capacity in 2010 by countries/regions, in percent; Source: Energy Information Administration (2010), EPIA (2010a), Emerging Energy Research (2010), Solarbuzz (2011)

In contrast to the market for PV installations, the production of solar cells – the key component of PV plants – mainly occurs outside of Europe. In recent years Asia has emerged as the major production hub for solar cells, accounting for more than ~60% of global production in 2009 (Photon 2010). Amongst other factors, this has been driven by favourable energy and labour costs as well as deep expertise in semiconductor technology. The majority of innovative activity in the field of PV technology has also occurred outside of Europe in recent years, with US, Japanese and Chinese inventors accounting for more than 50% of international patent families (Peters et al., 2011). While it was chiefly large technology providers (like Siemens) and energy companies (such as Shell and BP) which were the first to establish industrial scale production lines in the field of PV, at present the leading PV technology providers are mainly pure-play firms (e.g., First Solar, Suntech Power, SMA). Only in Japan have industry conglomerates such as Sharp or Sanyo been investing in PV technology for several decades.

2.2 *Concentrating Solar Power*

In the 1980s the first industrial scale CSP systems were built in the Mojave Desert using the parabolic trough design, which has remained the incumbent CSP design with market shares above 90% until today (CSP Today, 2010). However, three alternative CSP designs exist: tower, linear fresnel and dish engine. In a CSP tower, plant heliostats concentrate irradiation on one single receiver atop a tower. Due to the central receiver such systems benefit from higher steam cycle temperatures and lower energy transport requirements than parabolic trough plants. Land requirements, however, are significantly higher (Kaltschmitt et al., 2007). CSP plants using fresnel reflectors focus sunlight on an elevated linear receiver. Compared to a parabolic trough plant, linear fresnel systems exhibit lower costs for reflectors and structural support at the expense of lower solar-to-electric efficiencies (Purohit and Purohit, 2010). Dish engine systems consist of large mirror dishes and a receiver integrated with a combustion engine (e.g., a sterling engine) at the focal point of the dish. While dish engine systems are the most modular CSP design, investment cost and land use are high (Trieb, 2009).

As of 2010 1.3 GW of CSP capacity had been installed worldwide – significantly less than in PV (Figure 1). The majority of CSP capacity is installed in Spain, due to a favorable feed-in tariff (REN21, 2010) . However, future capacity additions are very likely to occur mainly outside of Europe since other geographies benefit from more favourable irradiation conditions and since Spain has capped annual CSP installations at 500 MW. In the US a multiple gigawatt (GW) project pipeline is expected to be executed in the coming years. Additionally the Middle East, North Africa, China and India all offer growth prospects for CSP (REN21, 2010).

CSP system and component providers are mainly based in Germany, Spain and the US. While German and Spanish CSP companies focus largely on the parabolic trough design (e.g., Siemens and Abengoa), US headquartered firms rather rely on power tower (e.g., Brightsource) and linear fresnel technology (e.g., Ausra). Until recently primarily startups and medium sized enterprises developed CSP technology. Yet since 2009 several leading European technology providers have invested in CSP firms: Siemens bought Solel, Areva acquired Ausra and Alstom invested equity in Brightsource.

3 Techno-economic assessment of solar power technologies – a review of the literature

In recent years various scholars have conducted techno-economic assessments of solar technologies. A focus of these analyses has been on the levelized cost of electricity since it is the key competitiveness metric for fossil-fired and renewable power generation technologies (Rubin et al., 2007; Sunpower Corporation, 2008). We compiled a comprehensive review of the recent literature, which uses LCOE as a metric in assessing solar power technologies (Table 1), allowing us to identify crucial research gaps. The aggregate analytical scope of the literature reviewed is quite broad. Analyses have focused on the three key determinants of LCOE, i.e., technology, time and location. Some studies complement the quantitative assessment with qualitative merit dimensions: Technological uncertainty (Sargent and Lundy, 2003), the addressable market (e.g., PricewaterhouseCoopers, 2010; Trieb et al., 1997), quality of electricity (e.g., Estela, 2010) and water requirements (e.g., PricewaterhouseCoopers, 2010; Trieb, 2009) are evaluated.

Integrating the existing studies into one overall picture is not possible since they rely on a variety of methods and partly inconsistent assumptions. In addition, some determinants of LCOE require further scrutiny. Eventually we identified four research gaps: First, there is a lack of literature assessing and comparing the two leading solar technologies, i.e., PV c-Si and PV CdTe on a granular level. Second, although most studies in the field of CSP include energy storage in their analyses (e.g., German Aerospace Center, 2006), this is not common in the field of PV – even though the intermittency of PV electricity is one of the major challenges of this technology (Trieb, 2009). Only recently have scholars begun to analyze storage options such as compressed air energy storage (CAES) and batteries (Estela, 2010; Mason et al., 2008) for PV. Third, while some scholars have run sensitivity analyses to understand the impact of variations in discount rate on LCOE (Pitz-Paal et al., 2005), location-specific realistic discount rates have not yet been included in LCOE analyses. Fourth, the extant literature also offers room for further enhancements of methodological rigor. Concerning the future cost reduction potential of solar technologies the majority of studies presented in Table 1 solely rely on a top down learning curve approach (IEA, 2010c; Kost and Schlegl, 2010), yet such a method is exposed to very high uncertainty in the field of solar technologies (Neij, 2008; Nemet, 2006). In addition, some studies are not very transparent regarding the underlying assumptions. For example, it is often unclear whether real or nominal price levels are used or whether CSP production figures are based on gross power sold, or net power after adjustment for purchased electricity.

As a result of technological uncertainty as well as the use of differing methods and assumptions, it is heavily contested among scholars and industry experts, which technology is and will prove most viable in electricity systems. Some years ago scholars agreed that the LCOE of CSP parabolic trough systems is significantly below that of PV plants (Quaschning, 2004; Trieb et al., 1997). This is also supported by the feed-in tariffs granted under the Spanish Royal decree 661 in 2007 and 2008 (Del Río González, 2008). However, significant cost reductions in the field of PV eliminated the former consensus (Sarasin, 2010). In very recent studies, which technologies offer and will offer the more competitive product in terms of LCOE is highly contested. For example, according to PricewaterhouseCoopers (2010) CSP LCOE is significantly below PV LCOE whereas Fthenakis and colleagues (2009) consider PV to be more competitive than CSP[1] in terms of LCOE. Furthermore, studies do not reach a consistent picture regarding the competitiveness of solar technologies with fossil based electricity generation. According to Estela (2010) and Trieb (2009) PV[2] and CSP will reach competitiveness with gas fired power plants between 2015 and 2020, while the IEA (2010b, c) expects competitiveness of PV and CSP plants past 2020. Assessing solar power generation technologies on a common basis and in a granular manner can help to shed some light on the research gaps presented above.

Table 1
Literature review on techno-economic assessment of solar power technologies

Publication	**Scope of LCOE analysis**		
	Technology (Storage)[a]	**Time**	**Variation of location variables (weather data, discount rate)**
Sargent and Lundy (2003)	CSP: parabolic trough, tower (yes)	2004, 2006, 2010, 2015, 2020	No
Quaschning (2004)	CSP: parabolic trough (no) PV: not specified (no)	2004, 2014	Weather data
Pitz-Paal et al. (2005)	CSP: parabolic trough, tower, dish engine (yes)	2005, 2020	Weather data; Discount rate (sensitivity analysis)
German Aerospace Center (2006)	CSP: not specified (yes)	2000 – 2050	Weather data
Ummel and Wheeler (2008)	CSP: not specified (yes)	2012-2020	No
Gerbert and Rubel (2009)	CSP: parabolic trough (?) PV: thin film (no)	2008	No
Trieb (2009)	CSP: parabolic trough (yes) PV: not specified (no)	2000-2050	Weather data (only CSP)
Fthenakis et al. (2009)	CSP: not specified (yes) PV: CdTe (yes)	2007, 2015, 2020	No
Landesbank Baden-Württemberg (2009)	CSP: not specified (?) PV: CdTe, CIGS/CIS, a-si/µ-si[b], c-Si (no)	2008 – 2020	Weather data (only for unspecified PV) technology)
Pricewaterhouse-Coopers (2010)	CSP: parabolic trough, tower (no) PV: not specified (no)	2010	Weather data (only CSP)
Purohit and Purohit (2010)	CSP: parabolic trough, tower (yes[c])	2007 (tower), 2009 (parabolic trough)	Weather data (only Indian locations)
Sarasin (2010)	CSP: parabolic trough, linear fresnel (no) PV: c-Si, CdTe (no)	2010	No
Izquierdo et al. (2010)	CSP: parabolic trough, tower (yes)	2005	No
Estela (2010)	CSP: not specified (yes) PV: not specified (yes)	2010-2025	Weather data
EPIA (2010b)	PV: not specified (no)	2010, 2020, 2030	Weather data
IEA (2010c)	PV: not specified (no)	2008, 2020, 2030, 2050	Weather data
IEA (2010b)	CSP: not specified (yes)	2010-2050	Weather data
Kost and Schlegl (2010)	CSP: parabolic trough, tower (yes) PV: not specified (no)	2010-2030	Weather data; Discount rate (sensitivity analysis)
Key message	No study models all leading solar technologies[d] incl. storage (i.e., PV c-Si, PV CdTe, CSP parabolic trough) • 1 study compares leading PV designs[d] (e.g., c-Si and CdTe) • 2 out of 18 studies analyze PV storage solutions	Most studies (13 out of 18) project future LCOE (some up to 2050)	No study accounts for deviations in country risk *and* weather data when modeling different locations • 12 out of 18 studies vary weather data • 2 out of 18 studies conduct sensitivity analyses of discount rates (no modeling of country risk)

a Type of solar technology modeled, in brackets: information regarding whether storage is modeled.
b Amorphous and micromorph silicon. c Tower: Storage < 1 hour. d In terms of capacity installed.

4 Methodology

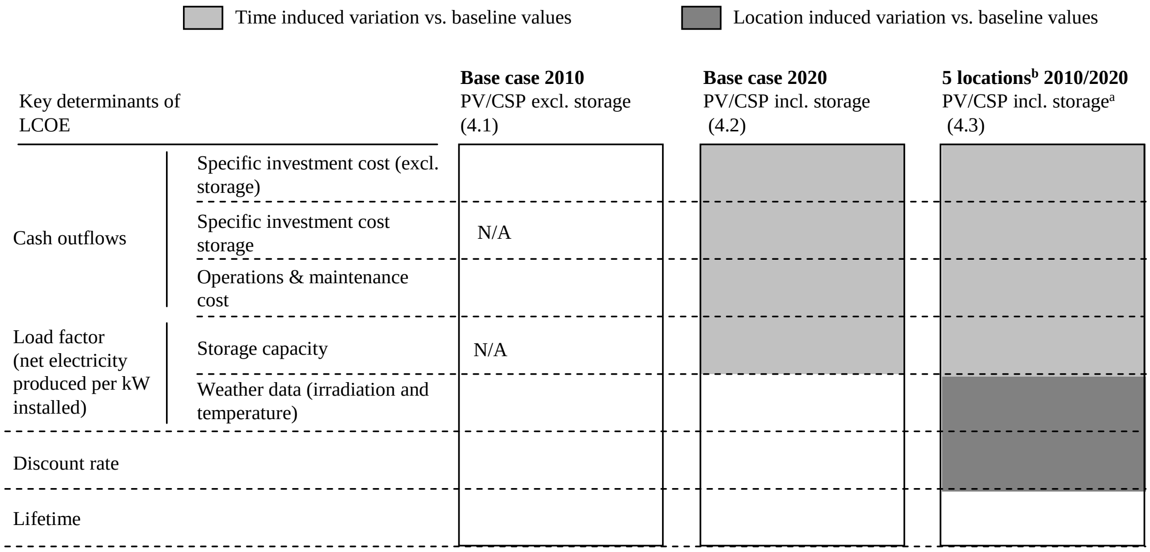
The subsequent section is very comprehensive in order to be transparent about our methodological approach. We scrutinized large-scale solar power plants based on the leading solar technologies (PV c-Si[3], PV CdTe and CSP parabolic trough)[4] by conducting a quantitative and qualitative techno-economic assessment. We identified cost and quality of electricity as the key merit dimensions, which we analyzed based on a LCOE model. The cost of energy storage is also included in the model as the storage capabilities of a power plant determine the quality of electricity. Concerning financing we assumed an unleveraged financing of the power plant assets. The discount rate is the pre-tax unsubsidized value in each country. We derived the following LCOE formula from the literature (Kost and Schlegl, 2010):[5]

$$\frac{\sum_{n=0}^{N}\frac{CAPEX+OPEX}{(1+i)^{n}}}{\sum_{n=0}^{N}\frac{kWh_{initial,net}\times(1-Degrade)^{n}}{(1+i)^{n}}} \qquad (1)$$

Where *CAPEX* (investment cost) and *OPEX* (operations and maintenance cost) represent cash outflows. The net electricity production[6] is determined by the initial production ($kWh_{initial,\ net}$) and the degradation factor (*Degrade*). i is the discount rate and n the plant lifetime.

To benchmark solar technologies we use the LCOE of a combined cycle gas turbine (CCGT). It is considered a reasonable yardstick for renewable electricity by public bodies in the US and Europe (California Public Utilities Commission, 2011; European Commission, 2010). In the US and in Europe gas-fired plants are projected to be the fastest growing non renewable source of electricity (Energy Information Administration, 2010). CAPEX assumptions are based on European Commission data (European Commission, 2008). In an upper LCOE bound we included a high CO_2 and gas price scenario, while for a lower bound we assumed no CO_2 prices and a low gas price scenario (see Appendix C for assumptions).[7]

In the subsequent subsections we outline the modeling of the key determinants of LCOE, which are dependent on technology, time and spatial parameters (Figure 2). In 4.1, we present the derivation of LCOE input data to assess PV and CSP plants excluding storage in a baseline location in 2010, namely Dagget (California, US). In 4.2, the methods used to project LCOE input data for solar power plants including storage built at the baseline location in 2020 are described. In 4.3, we provide details on the replication of the 2010 and 2020 LCOE analyses for additional locations in some of the largest present and/or future solar markets, i.e., China, Germany, North Africa and Spain. In the final subsection (4.4), we present how we qualitatively evaluated merit dimensions apart from generation and storage cost of electricity. For all operations and maintenance (O&M) cost an annual escalation in line with the long-term EUR inflation rate is assumed. Discount rates are also EUR inflation adjusted via the simplified Fisher equation (Fisher, 1930). All assumptions underlying the solar LCOE calculations are presented in the Appendix (Tables A.1-A.4 for PV technologies, Tables B.1-B4. for CSP parabolic trough, Tables D.1-D.2 for general assumptions).



a 2010 excl. storage. b Storage capacity of PV plants in Germany adapted to reach capacity factors in Spain.

Fig. 2. Overview of levelized cost of electricity (LCOE) model

4.1 Assessing the baseline location in 2010

To construct a base case we calculated present (2010) LCOE values for PV c-Si, PV CdTe and CSP parabolic trough plants in Daggett (California, US). Daggett was chosen as a baseline location for two reasons. First, it is representative for the Southwest of the US, which is likely to become the largest solar market in the medium-term (REN21, 2010). Second, Daggett is amongst the locations with the best solar resource in the world and thus well-suited to calculate the performance frontier of solar technologies. Furthermore, we did not incorporate storage solutions in the 2010 base case since this is not standard practice within solar power plants at present. This is due to the high cost of storage, low penetration of intermittent solar power and favorable feed-in tariff schemes, which guarantee the buy-off of intermittent power (REN21, 2010).

For all solar technologies we assumed identical discount rates, which reflect typical return requirements in the power industries of industrialized countries (Salomons and Grootveld, 2003). Plant lifetime is chosen based on typical assumptions in the PV industry (EPIA, 2010b) and does not vary between technologies, 2010 and 2020, or location.

4.1.1 PV c-Si and PV CdTe

Specific cash outflows

Cash outflows per kW depend on investment cost consisting of component cost, project development and EPC[8] cost as well as O&M cost. While investment cost per kW of PV plants are usually quoted based on gross values under standard test conditions we use net capacity to be consistent with CSP parabolic trough capacity, which is typically provided in net values.[9] For PV c-Si and CdTe component price assumptions we relied on investor reports of leading PV module and inverter companies (i.e., First Solar, Yingli, Suntech Power and SMA). Since current PV component profit margins partly differ significantly by company and component we calculated two cases, one based on "as is" profit margins the other based on expected long-term profit margins by component.[10] Expenses for project development and EPC cost were derived from First Solar investor communication, the world's leading CdTe module manufacturer. O&M cost are taken from EPIA (2010b) and expressed as a fraction of the initial investment on an annual basis.

Specific electricity production

The initial PV electricity production per kW_{net} depends on the solar resource available at a certain location and the outside temperature. Global solar irradiation consists of two components: direct and diffuse irradiation. PV converts both types of irradiation into electricity. We calculated the amount of solar irradiation received by a fixed module with optimal tilt based on global solar irradiation data.[11] We derived an average annual weighted module temperature factor based on dry bulb temperature data (U.S. DOE, 2011) for PV c-Si and PV CdTe in our baseline location.[12] Since the initial net electrical energy output of PV plants per kW slowly decreases over time we assumed a typical annual degradation rate of PV c-Si and PV CdTe module capacity (Jordan et al., 2010).

4.1.2 CSP parabolic trough

Specific cash outflows

We relied on investment cost data from the NREL Solar Advisor Model (NREL 2010) which splits up the cost of a wet-cooled 100 MW CSP parabolic trough reference plant in the Southwest of the US into roughly 50 cost items[13]. The profit margin of the EPC company is adapted to be in line with PV plants. Using scaling factors also provided by NREL (2010) we scaled the reference plant down to 50 MW – a typical size for a plant built in 2010 or in previous years. The NREL installation cost data is also consistent with the turnkey price of a recently commissioned CSP parabolic trough plant in the US, i.e., Nevada Solar One (64 MW). O&M cost data was taken from the European

Commission (2007) and expressed as a fraction of the initial investment on an annual inflation adjusted basis.

Specific electricity production

Unlike PV, CSP only makes use of direct irradiation. The amount of solar resource that hits the solar field aperture of a CSP system is given by the DNI (direct normal irradiation). Irradiation data was obtained from EnergyPlus weather data sets (U.S. DOE, 2011). We fed the NREL SAM model (NREL 2010) with the assumed DNI to thermodynamically model the net electrical energy output of the CSP parabolic trough plant. We optimized the field sizes via iterative model runs, ultimately choosing the configuration with the lowest LCOE.[14]

4.2 Assessing the baseline location in 2020

A replication of the base case in 2020 yields two time induced variations. First, the specific investment and O&M costs of solar technologies decrease due to technical and industry evolution. Second, PV and CSP power plants are assumed to have storage. Given the high uncertainty around cost estimates based on learning curve data (Nemet, 2006) we used – where possible – a bottom-up approach to estimate different sources of cost reduction (Neij, 2008). We considered three types of cost reduction: 1) R&D driven, i.e., technical improvements, 2) production driven, i.e., component cost reductions through economies of scale and learning-by-doing, and 3) scaling of power plant size (Sargent and Lundy, 2003). In the case of CSP we separately analyzed all three types. In the case of PV, R&D and production driven cost reductions were treated on an aggregate level for data availability reasons and cost reduction through scaling of plant size was not included due to the high modularity of PV power plants.

As the penetration of solar electricity increases, storage solutions will become ever more important for grid integration and matching of demand and supply. We modeled a molten salt storage solution in the case of CSP. For CSP we assumed six hours storage in all locations yielding load factors between 34% and 46%. For PV, a compressed air energy storage (CAES) is assumed, which is accepted as a low cost and widely available solution (Fthenakis et al., 2009). For each location we modeled PV CAES plants with six hours storage thus reaching the same level of electricity quality.[15] Since scholars also model CSP plants with more than six hours storage to approach base load profiles (e.g., Trieb et al., 2011) we, in addition, analyzed CSP and PV power plants with 16 hours storage (see Appendix E).

4.2.1 PV c-Si and PV CdTe including compressed air energy storage

Specific cash outflows excluding storage

We modeled future component cost and profit margins on a granular basis and kept the share of project development and EPC in the total investment cost constant. O&M cost for PV plants was also kept constant in terms of the annual fraction of the initial investment. Below we outline the methods used to derive PV c-Si and CdTe module prices as well as inverter and other component prices including R&D and production driven cost reductions.

We projected 2020 PV c-Si module prices by modeling silicon, silicon to wafer and wafer to module cost and profit margins[16]. To calculate future PV CdTe module cost we used First Solar's cost roadmap including R&D and production driven cost reduction potentials until 2014. Beyond 2014 we chose a learning curve approach[17]. Profit margin assumptions correspond to long-term expected profit margins in 2010 (see 4.1.1)

For both PV c-Si and CdTe, 2020 inverter costs were calculated based on the SMA specific learning curve observed between 2005 and 2009 assuming long-term expected profit margins. Remaining balance of system cost (BOS) was assumed to develop according to the First Solar technology roadmap until 2014. Thereafter, unit cost reduction was projected based on a learning rate calculated using prior cost reductions in BOS[18]. Our overall PV system costs estimates (c-Si and CdTe) for 2020 appear to occupy a middle ground between more aggressive (Fthenakis et al., 2009) and more conservative projections (IEA, 2010c).

Specific cash outflows CAES

Scholars widely agree that CAES and pumped hydro storage are the lowest cost options for large scale daily cycle electricity storage (Calaminus, 2010; Hannig et al., 2009; Leonhard W. et al., 2009). Both technologies are frequently cited as options to store intermittent PV and wind power (e.g., Mason et al., 2008). In this study we modeled CAES since underground storage capacity (e.g., in caverns) is widely available across the globe (Calaminus, 2010; Huang et al., 2009; Succar and Williams, 2008; Taylor and Halnes, 2010). Furthermore, we assumed that in 2020 advanced adiabatic (AA) CAES will be available (RWE, 2010)[19]. We used cost data on a component level (turbine, compressor, thermal storage and balance of plant) to model the 2020 cost structure of AA-CAES (Mason et al., 2008; Pickard et al., 2009). Our estimates are roughly in line with top down assumptions of AA CAES investment cost (e.g., Zunft et al., 2006).

Specific electricity production

To model PV power plants with load factors in the range of CSP plants, we increased the size of the PV field without increasing the nominal capacity of the total plant. Based on hourly EnergyPlus irradiation data (2010) we calculated the amount of electricity fed directly into the grid (i.e., up to the nominal capacity) and the amount which is stored beforehand. To calculate the electricity production of the PV plant the same method as in 4.1.1 was used. For electricity being channeled through storage the CAES efficiency factor was applied in addition.

4.2.2 CSP parabolic trough cost structure including molten salt storage in 2020

Specific cash outflows including molten salt storage

As in the case of PV we modeled future component costs on a granular basis and kept the share of project development and EPC in the total investment cost constant. O&M cost for PV plants was also kept constant in terms of the annual share of the initial investment. Below we present cost reduction potentials induced by R&D as well as by production and scaling of plant size.

Regarding R&D driven cost reduction, the most crucial technical lever to reduce cost per watt installed is an increase in steam cycle temperatures from what is today ~400°C to more than 500°C, which improves solar-to-electric efficiency. There are two technical pathways available to do so for which prototypes already exist (Archimede Solar Energy, 2011; Zarza et al., 2004). First, direct steam plants, second, plants in which salt is used as a heat transfer fluid. Since direct steam plants with storage units are still in an early research phase (Steinmann and Tamme, 2008) we modeled a molten salt system[20]. In addition, we assumed that today's two tank storage systems are replaced with a one tank thermocline solution further reducing cost per watt installed (Price et al., 2002).[21]

Primarily production driven cost reductions in the solar field and the HTF are calculated using a learning curve approach (Trieb, 2009) [22]. In contrast to PV, scaling of plant size is a crucial cost reduction lever in the case of CSP parabolic trough plants. The storage unit and the power block in particular benefit from larger plant scales. We used NREL scaling factors (2010) to model a plant size increase from 50 MW in 2010 to 300 MW in 2020.[23]

Specific electricity production

We used the NREL SAM model (NREL 2010) to calculate the electricity output of a CSP parabolic trough plant including six hours of molten salt energy storage. An LCOE optimal solar field size was chosen (compare section 4.1.2).

4.3 Comparative assessment of five locations in 2010 and 2020

Replicating the LCOE analysis for favourable locations (in terms of solar resource) in Spain, Germany, China and Egypt requires a variation in two input variables: discount rates reflecting local project risks and local weather conditions.[24] We assumed project risks to be the same in Spain, the US and Germany (Salomons and Grootveld, 2003) and used discount rates recommended by the UNFCCC for energy projects under the CDM in Egypt and China (UNFCCC, 2010). Local weather data was obtained again from EnergyPlus weather data sets (U.S. DOE, 2011). Based on this data we calculated location-specific temperature derate factors for PV plants. CSP solar-to-electric efficiencies are directly influenced by the amount of direct irradiation as well as the latitude determining the seasonality of irradiation. Therefore, using the NREL SAM model (2010) we iteratively optimized the solar field size of CSP systems in each location to always assure the lowest LCOE configuration.

4.4 Qualitative assessment of technologies

In a first step we selected merit dimensions other than cost using archival as well as interview sources. Based on the literature reviewed in section 3 (i.e., academic studies, industry reports) and three discussions with solar industry experts of about one hour each, we compiled seven qualitative merit dimensions: 1) technological uncertainty, 2) long distance transmission, 3) storage potential, 4) resource bottlenecks, 5) addressable market, 6) environmental impact and 7) potential for local value creation and employment. We chose these dimensions as they, according to the literature and industry experts, are or will become relevant for users, investors, technology providers and policymakers in terms of investment and policy funding. In a second step, we assessed PV c-Si, PV CdTe and CSP parabolic trough technologies along the above merit dimension using the same sources as in step one. For each dimension – if possible – the technology with a competitive advantage was selected based on industry expert knowledge.

5 Results

The results chapter is structured along the four research questions presented in chapter 1. In 5.1-5.3 we compare the solar LCOE results against the CCGT benchmark. In 5.4 we conclude with the results of the qualitative assessment.

5.1 Baseline location 2010

Figure 3, showing the LCOE for Daggett-based PV c-Si, PV CdTe and CSP parabolic trough plants in 2010, yields two key insights. First, compared to the benchmark technology CCGT solar technologies are 80% to 200% more expensive. Second, assuming long-term profit margins of manufacturers the current competitive advantage of PV CdTe becomes apparent. In 2010 PV CdTe LCOE are 11% below PV c-Si and 20% below CSP parabolic trough. Due to the leading cost structure of PV CdTe systems CdTe module manufacturer First Solar can currently charge substantial profit margins. These results should contribute to resolving the current debate as to which solar technology is currently best in terms of LCOE.

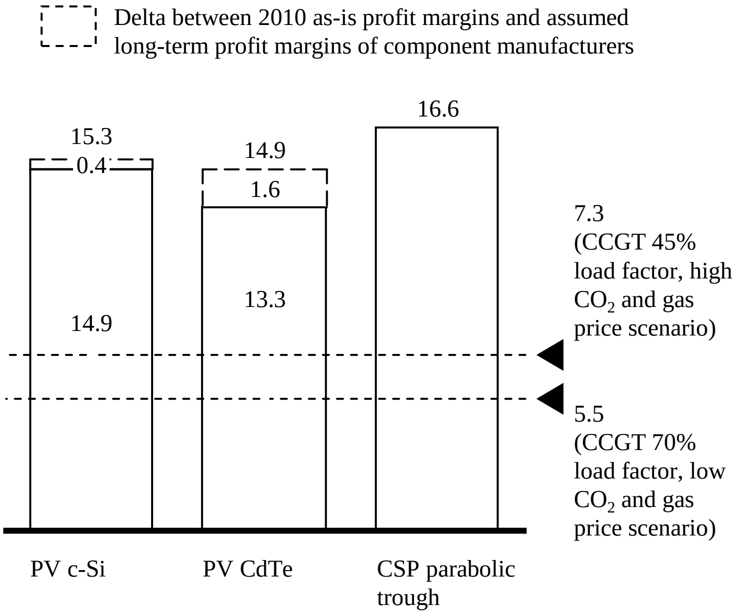


Fig. 3. Levelized cost of electricity (excluding storage) in 2010, Daggett (US), EUR$_{2010}$ cents/kWh

5.2 Baseline location 2020

Figure 4 shows the LCOE for Daggett-based PV c-Si, PV CdTe and parabolic trough plants in 2020. Three key findings emerge: First, solar technologies approach LCOE parity with CCGT due to decreases in solar LCOE and increases in the benchmark driven by rising gas and CO_2 prices. CSP parabolic trough plants including storage miss the upper bound of CCGT LCOE by less than 5%. Second, compared to the 2010 cost of PV and CSP peak electricity has decreased by 36-39%. Therefore, in terms of peak load PV CdTe clearly remains the leading technology. Third, however, the integration of six hours storage significantly increases LCOE of PV c-Si (+37%) and PV CdTe (+39%), while CSP LCOE only increases by 4%. Including storage CSP now has a 18% cost advantage over PV c-Si and 9% over PV CdTe. In the case of 16 hours storage this cost advantage is even more pronounced (see Appendix E).

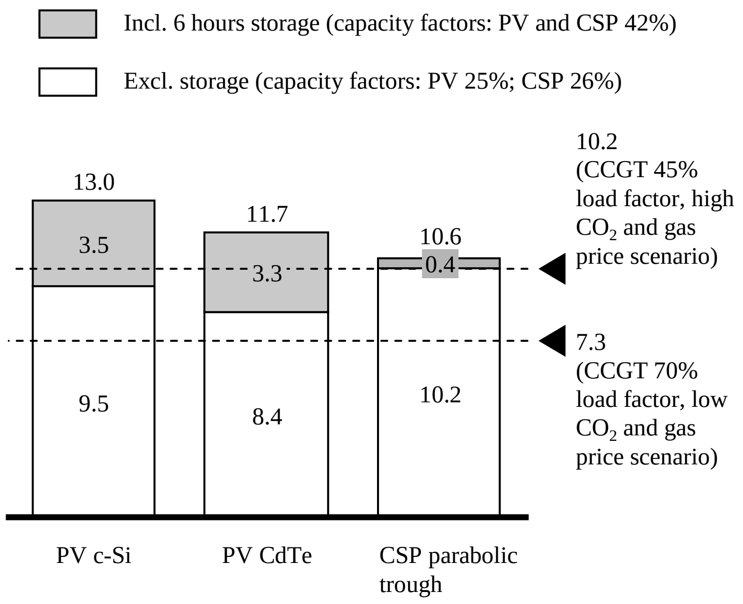


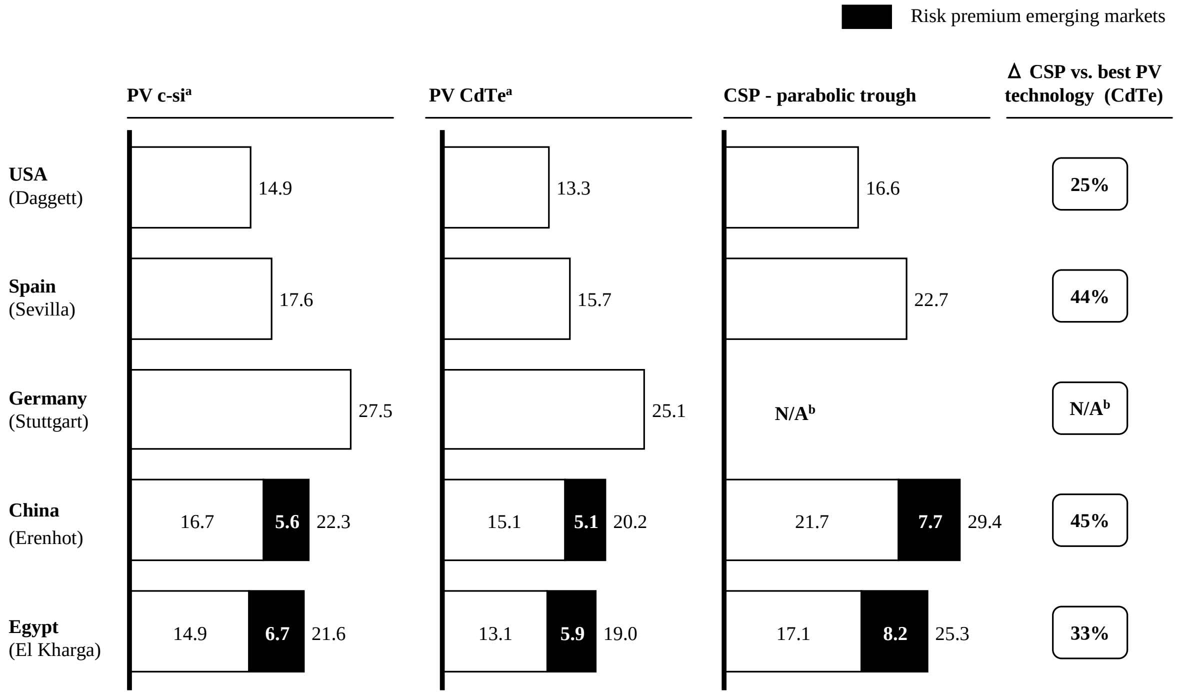
Fig. 4. Levelized cost of electricity in Daggett (USA), 2020, EUR_{2020} cents/kWh

5.3 Different locations in 2010 and 2020

We now extend the analyses in sections 5.1 and 5.2 to different locations. In Figure 5 and Figure 6 the 2010 and 2020 LCOE of PV c-Si, PV CdTe and CSP parabolic trough plants in present and future leading solar markets are exhibited. With regard to cross country comparison in 2010, the LCOE differences between the best (USA) and worst location (Germany)[25] reach almost to factor 2 driven by differences in weather conditions. However, due to disparities in local policy schemes Germany accounts for 40% and the US for only 7% of globally installed solar capacity (compare Figure 1).

Although irradiation conditions in China and Egypt are favorable, LCOE in these locations cannot compete with US LCOE due to additional country risk premiums, which increases LCOE by 34%-48%[26] and are caused by higher political, legal and regulatory uncertainties (UNEP and EcoSecurities, 2007). Excluding this premium, LCOE in the Egyptian location would be comparable to the US location. While the plants in the Spanish location do not have a country risk disadvantage, less favorable weather conditions result in LCOE being 18% (PV c-Si) to 37% (CSP) above US LCOE. The relative LCOE deltas between countries remain approximately stable until 2020.

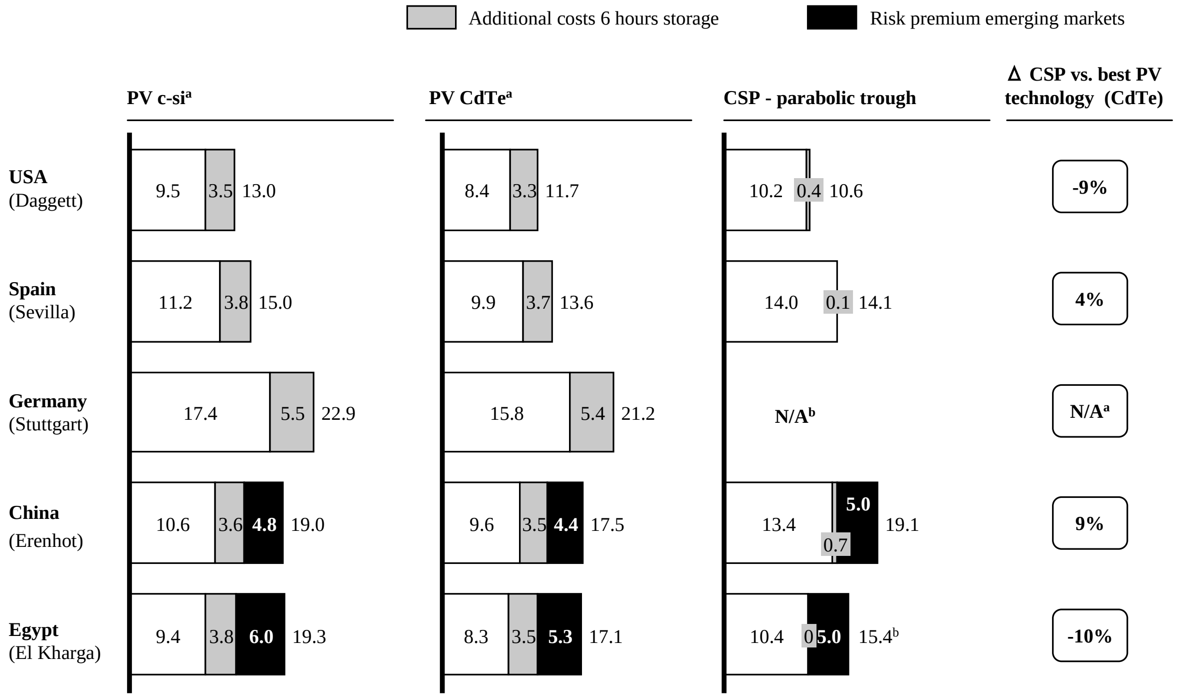
With regard to the solar technology comparison in 2010, in all locations PV CdTe ranks 1st, PV c-Si 2nd and CSP 3rd, with PV c-Si being 10%-13% more expensive than PV CdTe and CSP being 25%-45% more expensive than PV CdTe. However, in the US and Egypt the competitive advantage of PV over CSP is smaller than in Spain or China. This is due to higher solar-to-electric efficiencies of CSP in these locations caused by a higher share of direct irradiation and lower latitudes as well as higher temperatures reducing the efficiency of PV power plants. In 2020, driven by the integration of storage, CSP outperforms PV in two locations (US, Egypt). The delta between CSP and PV CdTe ranges from -10% to 9%. The LCOE difference between PV CdTe and PV c-Si remains stable PV c-Si being 10% to 14% more expensive.



a Based on assumed long-term inverter and module margins

b DNI in Germany (~2 kWh/sqm per day) is not sufficient to effectively operate a CSP plant. Scholars usually cite a threshold of 5 kWh/sqm per day

Fig. 5. Levelized cost of electricity (without storage) in 2010 by country, EUR_{2010} cents/kWh



a DNI in Germany (~2 kWh/sqm per day) is not sufficient to effectively operate a CSP plant. Scholars usually cite a threshold of 5 kWh/sqm per day
b 15.6 excluding storage

Fig. 6. Levelized cost of electricity in 2020 by country, EUR_{2020} cents/kWh

Regarding the benchmark with CCGT in 2010, solar technologies in all locations are not yet competitive. This is illustrated by the fact that even in the US Southwest – the location with the lowest LCOE – (see 5.1) solar power cannot yet compete with CCGT. Even in geographies with relatively high gas prices such as Europe, the upper bound of our LCOE calculations remains below 10 EUR cents/kWh. In countries like Egypt which have enacted fuel subsidies (Wuppertal Institut für Klima Umwelt Energie, 2006) CCGT LCOE are below the US level. In 2020, however, solar LCOE in the US and Spain approach parity with CCGT. While for the US this is already shown in 5.2, our analyses for Europe yielded a CCGT LCOE band of 8.3 to 12.2 EUR cents/kWh, which is in the range of solar peak load LCOE in Spain. In Germany, solar LCOE is still clearly above the benchmark. Gas price forecasts for Egypt and China are not available. Yet even assuming the relatively high European benchmark, solar LCOE in Egypt and China do not yet reach parity with CCGT.

5.4 Qualitative assessment

In light of the close competition between solar technologies in the field of LCOE, a complementary qualitative assessment is important. The results of the qualitative analysis are presented in Table 2. There is also no clear winner amongst the technologies on a qualitative level. CSP parabolic trough has a competitive advantage in two out of seven dimensions (storage potential 6-16 hours, long distance transmission, local value creation/employment). Vice versa also PV c-Si and CdTe outperform CSP in three out of seven dimensions (technological uncertainty, resource bottlenecks and addressable market). In the short- to medium-term there is no indication for issues that could severely challenge the technological evolution of PV c-Si, PV CdTe and CSP parabolic trough.

As in the case of LCOE, the relative competitiveness of CSP vs. PV improves at sites with a high and constant solar resource (e.g., Egypt, Southern California). At such sites the CSP parabolic trough could, in contrast to PV, generate more than medium load power at limited or no additional LCOE (see Appendix E). In addition, such locations are typically remote from load centers and thus require long distance transmission. This is cheaper for CSP parabolic trough plants where no local PV electricity storage is available.

Table 2: Qualitative assessment of solar technologies

Merit dimension	PV c-Si	PV CdTe	CSP parabolic trough	Technology with competitive advantage
1) Technological uncertainty	• Power generation: track record of cost reductions; 41 GW_{gross} deployed; • Storage: immature and costly; future cost downs highly dependent on (uncertain) technological breakthroughs		• 1 GW_{net} deployed; limited track record of cost reductions • High share of future cost reductions based on technological breakthroughs (power generation and storage)	PV (c-Si, CdTe)
2) Costs transmission over 3000 km (e.g., from Middle East/North Africa to Europe)	• 10% of LCOE due to losses • ~1 EUR cents/kWh for HVDC[a]; higher in case no storage at site possible due to lower utilization of HVDC		• 10% of LCOE due to losses • ~1 EUR cents/kWh for HVDC equipment	CSP
3) Storage potential 6-16 hours	• Yes, in geographies with high and constant solar resource • Increase in LCOE		• Yes, in geographies with high and constant solar resource. • Limited/no additional LCOE	CSP
4) Resource bottlenecks				PV c-Si
Water	• Negligible water consumption, aptitude for desert climates		• Wet cooled: high water consumption (~4,000 l/MWh), limited aptitude for desert climates • Dry cooled (increases LCOE by 3-8%): low water consumption (300 l/MWh); aptitude for desert climates	
Material for key Components	• Key materials (e.g., silicon) abundant	• Tellurium rare; yet, annual production potential > 100 GW likely	• Key materials abundant	
5) Addressable market				PV (c-Si, CdTe)
Modularity	• Very high; useful for central (> 100 MW) and decentral energy systems (<10 kW, e.g., for rural electrification, roof top applications)		• Low; plant size > 50 MW	
Geographies	• Viable also outside of sunbelt due to use of direct and indirect irradiation		• Not viable outside of sunbelt as direct irradiation required	
Combination with fossil-based power plants	• Not possible		• Possible, e.g., solar field used to preheat steam in order to save fossil fuel	
Slope angle restrictions	• None		• Up to 2° possible	
Side products	• None		• Waste heat can be used for desalination, process heat and cooling	
6) Environmental impact[b]				None
Life cycle greenhouse gas emissions[c]	• Low: 2010 ~ 25 kg/MWh	• Very low: 2010 ~ 15 kg/MWh	• Very low: 2010 ~ 15 kg/MWh	
Toxicity	• No/very limited use of toxic materials"	• Cadmium highly toxic; discharge very unlikely due to encapsulation in modules; recycling industry standard	• Thermo oil (at present standard heat transfer fluid) toxic. In the future, potentially to be replaced with non-toxic fluids (e.g., molten salt)	
Land use[c]	• 99 kWh/sqm p.a.	• 72 kWh/sqm p.a.	• 96 kWh/sqm p.a.	
7) Local value creation/employment opportunities	• High skilled work force: high (R&D, manufacturing) • Low skilled work force: low (installation[d])		• High skilled work force: Medium (R&D, high-tech manufacturing) • Low skilled work force: Medium (low-tech manufacturing, installation[d])	None

a High Voltage Direct Current (HVDC) line with 45% load factor. b For water consumption see resource bottlenecks.
c Values based on location in California, 2010. d Installation of CSP plant more labour intensive than installation of PV plant.

Source: The World Bank (2011); First Solar (2009); IEA (2009); Fthenakis (2009); Trieb (2009); Renewable Energy World (2010); Power Technology (2011); NREL (2011); German Aerospace Center (2006); Sargent and Lundy (2003); Estela (2010); Trieb et al. (1997); (Turchi et al., 2010); own calculations.

6 Policy implications

Solar power technologies will have to become a major pillar in the world’s future energy system to mitigate environmental problems such as resource scarcity and climate change. However, large-scale solar technologies cannot yet compete with fossil-fired electricity generation technologies. Thus, in order to foster and exploit the ‘solar option’ smart policy action on global and national levels is required. Essentially, four aspects must be addressed that relate to the main variables analyzed above. First, further policy support should incentivize innovators to exploit the technology-specific learning potentials in the field of PV and CSP technologies. Second, capitalizing on the solar resource available in sunbelt countries is crucial in order to efficiently deploy large-scale solar technologies. Third, policymakers can increase the efficiency of policy support by incentivizing investors and technology providers to exploit location-specific strengths of PV and CSP technologies. Fourth, due to the substantial cost, which is still involved in supporting these technologies at present, policymakers need to assess whether there are strategic co-benefits that enhance the political feasibility and stability of such support. Below, we discuss these four dimensions by relying on the quantitative and qualitative results obtained. This allows us to provide policy recommendations on how to unleash the potential of solar power.

Improving solar power technologies

Our analyses show that solar power technologies in the US and Spain are likely to approach competitiveness with fossil-fired generation by around 2020. Hence, policy support will be indispensable until at least 2020 for enabling innovation and deployment in the field of solar technologies. This will involve the creation of markets (e.g., via feed-in tariffs) as well as public R&D funding. The results of our study also underscore the fact that a dominant design in the field of solar power technologies is not yet emerging: In 2020 the LCOE of different solar technologies are rather close and their absolute levels are subject to technological uncertainty. Also the qualitative assessment does not yield a technology with a clear competitive advantage. For the policymaker this implies a need to maintain and develop a variety of technologies, otherwise the risk of picking the “wrong” design as a winner increases.

Moreover, the policymaker should account for varying improvement potentials by technology, which implies the need for tailoring policy schemes to specific technologies. Regarding LCOE reduction we pointed out the three principal potentials: R&D driven, production driven and scaling of power plant size. We show that in the case of CSP the scaling of plant size from 50 MW to 300 MW and R&D efforts targeting technological breakthroughs are crucial to reduce LCOE. Hence, policymakers should – unlike in the Spanish feed-in tariff regime – enable and incentivize large plant sizes. In addition, public R&D funding is important to support the high risk, high return R&D projects which contribute to technological breakthroughs. While our analysis indicates that the scaling of PV power plants beyond 50 MW has little effect on LCOE, R&D efforts and the scaling of production reduces LCOE. Finding an adequate balance between public R&D funding and deployment policies such as feed-in tariffs and designing more efficient deployment policy schemes in terms of innovation effect are the key challenges for policymaking in this context (Peters et al., 2011). In addition, the increasing share of solar and other intermittent renewable electricity calls for action: Policymakers ought to intensify policy support for storage and demand side management technologies, as well as enact regulations which simplify and incentivize the integration of such technologies into the grid, for example, dedicated public R&D funding for smart grid technologies and a feed-in tariff premium for stored electricity.

Efficiently deploying large-scale solar technologies by capitalizing on the solar resource

Our results clearly indicate that the location variables solar irradiation, discount rate and fuel prices heavily influence the competitiveness of solar power compared to a market benchmark. We show that the competitiveness of solar technologies is best in developed countries with a good solar resource and high fossil-fuel prices. Therefore, deploying solar power in the Southwest of the US or Spain is significantly more efficient than in Germany as it causes lower costs to society. In this respect the current distribution of installed PV capacity presented in 2.1 is highly suboptimal. Our 2010 LCOE results imply that in Germany the required feed-in tariff per kWh is around three times higher than in the Southwest of the US. While in the past in particular solar feed-in tariffs in Germany triggered the flourishing of the global PV market, in the years to come countries with an attractive solar resource should ideally drive the deployment of large-scale solar technologies.

Our analyses point out that relatively high discount rates and fuel subsidies put solar technologies at a significant disadvantage in emerging economies such as Egypt – despite their substantial solar resource. If these countries aim to develop a green growth strategy (Project Catalyst, 2010), for example under the UNFCCC, several levers could be pulled to increase the attractiveness of solar technologies. Our analyses indicate for example that excluding country risk premiums solar LCOE in Egypt would be comparable to the level in the US Southwest. Thus, policymakers should focus on reducing or taking over project risks in emerging countries in order to improve LCOE. Governments of emerging economies could act as investors themselves as illustrated by the Chinese state, employ governmental low-interest loans and provide state guarantees in combination with an international insurance for long-term power purchase agreements (Trieb et al., 2011). A second important lever is the gradual removal of fossil fuel subsidies, which is however an intricate endeavor. All these activities could be internationally supported, e.g. via the Clean Technology Fund of the World Bank or the Green Climate Fund established under the UNFCCC. Also bilateral support from developed countries is conceivable. For some developed countries with a limited solar resource there is a particular rationale to provide financing as they could import solar electricity from emerging economies in the sunbelt (e.g., within the scope of the Desertec project).

Exploiting location-specific strengths of PV and CSP technologies

For policymakers an understanding of the location-specific strengths of different solar technologies is key in order to focus on the most competitive technology for the respective location. In this context, three key findings emerge from our research. First, in locations with a relatively high share of diffuse irradiation, medium average temperature and a latitude of above 35 degrees such as Spain and Inner Mongolia in China our research suggests that policymakers and investors should focus on PV technologies. Second, locations with a high share of DNI, high temperatures and low latitude such as the Southwest of the US or Egypt are relatively favourable for CSP. In 2020 CSP is more competitive than PV in such locations if storage is included in plants. In addition, our research indicates CSP, in contrast to PV, can offer storage at no or only very limited additional costs in such locations. Hence, in these geographies CSP should account for a substantial share in the solar portfolio. However, water scarcity in the Southwest of the US and in North Africa could require CSP plants to be air-cooled, increasing LCOE by around 3-8% vs. wet-cooled systems (Turchi et al., 2010). Third, the choice of solar technology depends on the value of storage at a specific location. If solar power is deployed in a market with a low share of intermittent electricity where storage is not yet required PV is more attractive than CSP due its lower peak load LCOE. If the share of intermittent electricity, however, is high and thus storage is valuable CSP gains a competitive edge due to its limited LCOE increase due to storage.

Strategic search for co-benefits to increase political feasibility of solar power

To lead solar technologies towards competitiveness significant policy support is still needed, which will be paid for society. Therefore, political feasibility of solar support plans might be limited due to public acceptance issues. The results of our qualitative assessment are helpful in deriving three strategic co-benefits, which could increase the political feasibility of solar power. First, the diffusion of solar technologies in a country has the potential to offer local value creation and employment opportunities in R&D, manufacturing and installation. To exploit this potential a country should consider its specific competences when selecting a solar design. For example, if labor in a country is rather low skilled and low cost, CSP could offer more local value creation and employment opportunities than PV since CSP is more labor intensive and requires a less skilled workforce than in the case of PV. If a country lacks key competencies to establish a successful domestic industry in the field of PV or CSP, it could strive for acquiring such competencies through, e.g., funding public R&D or other capacity-building measures before investing significant funds in market creation. If successful, such strategies could allow a country to increase local value creation.

Second, solar power cannot only be deployed centrally in large-scale plants, but -in the case of PV- also in highly modular decentral generation units. It is widely accepted that in the emerging and least developed countries rural electrification can significantly contribute to economic development. As a result, in such countries policymakers should not exclusively focus on large-scale applications but also on rural electrification to generate ‘high value’ electricity.

Third, on an international level policymakers could strive for finding synergies between industrial strategies. The Desertec project is potentially a prominent example for bilateral synergies in this context. European states are likely to pay the majority of policy support needed to realize the project. This ’investment’ translates into business for the companies in the Desertec consortia. In addition, Europe benefits from excellent irradiation conditions and low labor cost in the Middle East North Africa (MENA) region. Conversely, MENA states will gain from additional power supply, local value creation and employment. On the multilateral level, i.e., especially within the UNFCCC discussions, countries should develop roadmaps for the diffusion of solar technologies, reflecting their specific situation regarding natural resources, and social and techno-economic aspects. International institutions such as the Technology Executive Group or the Green Climate Fund, which are to be founded according to the Cancun agreement, should then coordinate and in the case of non-OECD countries financially support these activities.

7 Conclusion

This paper addressed a gap in the current discussions on the potential role of solar power technology in the world’s energy systems by providing a comparative assessment of the three leading large-scale solar technologies in 2010 and 2020 as well as for different locations. We show that today these technologies cannot yet compete with conventional forms of power generation but approach competitiveness around 2020 in favourable locations. In addition, we find that none of the solar technologies emerges as a clear winner and that costs of storing energy differs by technology and can change the order of competitiveness in some instances. Importantly, the competitiveness of the different technologies varies considerably across locations due to differences in, e.g., solar resource and discount rates.

Based on these results we derive four policy implications. First, policy support should facilitate the implementation of cost reduction levers and enable the integration of solar technologies on a system level. Second, policymakers ought to increase the efficiency of policy support by particularly fostering solar market growth in countries with an attractive solar resource. Third, the exploitation of location-specific strengths of PV and CSP technologies could further increase the efficiency of policy support. Lastly, policymakers need to leverage strategic co-benefits of solar power deployment in order to enhance the political feasibility and stability of policy support.

In order to further refine policy recommendations, some areas for future research are especially promising. Policymakers need to be assisted by coming up with more precise advice on which policy mixes are most warranted to improve the different technologies, which are subject to different underlying learning mechanisms. In addition, while this study has shed light on the competitiveness of typical solar power plant projects, more detailed analyses of the total potential for these technologies in different countries are required. Lastly, future research should support policymakers in exploiting this potential by evaluating in more detail the needs for accompanying measures in the areas of storage and grid management.

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[1] 2007, excluding storage, California.

[2] Excluding storage.

[3] There are two types of c-Si multicrystalline and monocrystalline. As multicyrstalline has the higher market share our analysis is based on multicrystalline silicon.

[4] We focused on large-scale solar power plants for two reasons. First, as CSP plants are of large scale[4] it allows for a fair comparison between CSP and PV technologies. Second, in 2010 "the trend toward large-scale PV plants continued around the globe" (REN21, 2010, p.19).

[5] A salvage value of 0 is assumed at the end of a plant's lifetime; potential LCOE reduction effects of carbon credits are not included since a CO_2 price is already reflected in the benchmark technology.

[6] It is assumed that electricity consumed at site is covered by electricity produced at site and not by purchased electricity.

[7] When comparing solar technologies with the benchmark two aspects should be considered. First, the quality of CCGT electricity is higher than of any solar technology: CCGT can offer full load at any time of the year while solar plants with storage at most locations are at times – particularly during the winter months – not capable of operating at full load. Second, however, LCOE of CCGT plants heavily depends on fuel and CO_2 price developments and hence is more uncertain.

[8] Engineering, procurement and construction.

[9] Differences between PV net and gross values are particularly driven by soiling and inverter losses.

[10] This particularly allows for the reflection of significant profit margin differences between PV c-Si and CdTe modules, thus better reflecting the intrinsic LCOE performance of PV c-Si and CdTe.

[11] Irradiation data was obtained from EnergyPlus weather data sets (U.S. DOE, 2011). It provides TMY (typical meteorological year) weather data with an hourly resolution for more than 2100 locations worldwide. Data is either based on long-term ground measurement or on satellite derived data in combination with ground measurement. We cross-checked irradiation data for our locations with specific project data (Cohen, 2008; Solar Millennium, 2008) and alternative meteorological data (Joint Research Centre European Commission, 2011; Meteotest, 2010). Deviations were below 15%.

[12] The temperature within PV modules can account for performance variations of more than 10%.

[13] As there is hardly any information on profit margins in the CSP industry available we do not model profit margins separately as in the case of PV. However, we assume that implicit component profit margins in the NREL data are rather on the low end given that CSP in the US faces significant competition from other power technologies such as wind and PV.

[14] "SAM is based on an hourly simulation engine that interacts with performance, cost, and finance models to calculate energy output, energy costs, and cash flows." (https://www.nrel.gov/analysis/sam/). In the case of CSP plants the SAM performance model also considers thermodynamic parameters. For each location (USA, Egypt, China and Spain) we integrated EnergyPlus weather data in the model and specified the type of storage (no storage, six hours storage). We then iteratively optimized the solar field to generate the LCOE optimal plant design.

[15] As we do not model a CSP plant in Germany, we assumed the Spanish load factor (34%) for the PV plant in Germany.

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[16] Silicon cost estimates are based on a medium-term forecast by LBBW (2009). Specific silicon utilization per watt is projected by accounting for higher efficiencies, thinner wafers and reduction in kerf loss (Mason, 2007). Silicon to wafer cost and wafer to module costs are forecasted by applying a typical PV c-Si learning rate.

[17] Based on 2005-2009 First Solar production data we computed a PV CdTe module learning rate, which we used to estimate cost reductions between 2014 and 2020.

[18] In addition, BOS cost reductions driven by increases in module efficiency are considered.

[19] Compared to today's diabatic CAES technology this solution is likely to need no gas firing and round cycle efficiencies are significantly higher.

[20] Further technical measures include front surface mirrors, which improve the optical efficiency of the solar field. Overall, we assumed a solar-to-electric efficiency increase to 19% in the baseline location (see also Table B.3).

[21] A single tank storage energy system, which uses a low-cost filler material to replace the more expensive molten salt (35% cost reduction$_{\text{real}}$). Using molten salt has further positive and negative effects on investment costs, which we assume to offset each other. On the one hand such systems offer additional cost reduction potentials since less molten salt is needed due to higher temperatures and heat exchangers can be displaced. On the other hand, higher temperatures could require the use of more costly materials and O&M costs could increase as at times gas firing might be needed to prevent molten salt from freezing in the receiver tubes.

[22] For the HTF and the solar field a 10 % learning rate$_{\text{real}}$ is assumed; for the power block a constant annual unit cost reduction of 2% is assumed as cost reductions$_{\text{real}}$ for steam power blocks are rather driven by developments of conventional electricity technology.

[23] The scaling effect is calculated as follows: (baseline plant cost) x (project plant size / baseline plant size)^(scaling factor); assumed scaling factors: solar field (1), except civil work (0.9), power block (0.8), HTF (0.9) except solar field piping and HTF fluid (1), storage (0.8) except storage fluid (1).

[24] In addition, construction and project development cost differ between locations as they are dependent on local labour and permitting cost. However, as these costs are below 20% of the total PV and CSP system prices we assumed these costs to be the same across all locations (NREL, 2010).

[25] Feed- in tariffs for large-scale open-space PV power plants ranged between 25.4 and 24.3 EUR cents/kWh in 2010. While this is below the c-Si LCOE value in Figure 5, a market for such installations still existed since investors accepted an unleveraged internal rate below 8%.

[26] The risk premium in China relates to private investments. State investments or investments being backed by the state, a common practice in China, will have a lower risk premium. For example, First Solar's 2 GW Ordos project is backed by the city of Ordos.

Appendix A

Table A.1
Investment cost PV power plant and adiabatic compressed air energy storage (AA-CAES)

	PV c-Si		**PV CdTe**		**Source**
	2010	**2020**	**2010**	**2020**	
PV power plant investment cost excl. storage, EUR/watt$_{gross}$	2.32	1.47	2.13	1.35	
Module price	1.23	0.77	0.89	0.56	See manufacturing costs & margins
Inverter price	0.19	0.16	0.19	0.16	See manufacturing costs & margins
Balance of system price (excl. inverter)	0.64	0.32	0.80	0.41	First Solar (2009), EPIA (2004), own assumptions & calculations
Project development cost, EUR/watt$_{gross}$	0.09	0.10	0.09	0.10	First Solar (2010a)
EBIT Engineering, Procurement and Construction (EPC)	0.19	0.12	0.17	0.11	See manufacturing costs & margins
PV power plant manufacturing cost & margins					
Module manufacturing cost CdTe, EUR/watt$_{gross}$ (excl. overhead)	N/A	N/A	0.54	0.34	First Solar (2010b), First Solar (2009), EPIA (2010a), First Solar annual reports 2005-2009, own calculations
Module manufacturing CdTe gross-margin	N/A	N/A	39%	39%	First Solar (2010b), own assumptions
Module manufacturing (vertically integrated) EBIT-margin	22%	22%	22%	22%	Yingli Green Energy (2011), own assumptions
Silicon manufacturing cost (incl. overhead)	0.12	0.06	N/A	N/A	Landesbank Baden-Württemberg (2009), Mason (2007), EPIA (2004)
Silicon manufacturing EBIT-margin	30%	30%	N/A	N/A	own assumptions
Silicon to wafer manufacturing cost (incl. overhead)	0.33	0.21	N/A	N/A	Landesbank Baden-Württemberg (2009), Strategies-Unlimited (2003), EPIA (2010a)
Silicon to wafer manufacturing EBIT-margin	15%	16%	N/A	N/A	own assumptions
Wafer to module manufacturing cost (excl. overhead)	0.40	0.26	N/A	N/A	Suntech Power (2010), Strategies-Unlimited (2003), EPIA (2010a)
Wafer to module manufacturing cost gross-margin	19%	19%	N/A	N/A	Suntech Power (2010), own assumptions
Wafer to module manufacturing cost EBIT-margin	11%	11%	N/A	N/A	Suntech Power (2010), own assumptions
Inverter manufacturing cost, EUR/watt$_{net}$ (excl. overhead)	0.16	0.14	0.16	0.14	SMA (2010); SMA annual reports 2006-09, EPIA (2010a)
Inverter manufacturing gross-margin	21%	21%	21%	21%	SMA (2010), own assumptions
Inverter manufacturing EBIT-margin	10%	10%	10%	10%	own assumptions
EPC-margin	8%	8%	8%	8%	own assumptions
Advanced adiabatic CAES investment costs (6 hours storage)					
CAES turbo generator, EUR/watt$_{net}$		0.18		0.18	Mason et al. (2008)
CAES compressor, EUR/watt$_{net}$		0.16		0.16	Mason et al. (2008)
Balance of system (Compressor to generator ratio = 1)		0.12		0.12	Mason et al. (2008)
BOS % increase per increase of compressor to generator ratio by 1%		64%		64%	Mason et al. (2008)
Scale up factor PV power plant – US		1.85		1.80	own calculations
Scale up factor PV power plant – Spain		1.75		1.70	own calculations
Scale up factor PV power plant - Germany		2.75		2.75	own calculations
Scale up factor PV power plant - China		1.65		1.60	own calculations
Scale up factor PV power plant - Egypt		2.1		2.00	own calculations
Compressor to generator ratio - US		0.85		0.80	own calculations
Compressor to generator ratio - Spain		0.75		0.70	own calculations
Compressor to generator ratio - Germany		1.75		1.75	own calculations
Compressor to generator ratio - China		0.65		0.60	own calculations
Compressor to generator ratio - Egypt		1.1		1.00	own calculations
Cavern storage cost (6 hours)/watt$_{net}$ installed		0.01		0.01	Mason et al. (2008)
Thermal energy storage (6 hours)/watt$_{net}$ installed		0.36		0.36	Pickard et al (2009)
CAES investment cost US, EUR/watt$_{net}$		0.80		0.78	own calculations
CAES investment cost Spain, EUR/watt$_{net}$		0.77		0.76	own calculations
CAES investment cost Germany, EUR/watt$_{net}$		1.01		1.01	own calculations
CAES investment cost China, EUR/watt$_{net}$		0.75		0.74	own calculations
CAES investment cost Egypt, EUR/watt$_{net}$		0.86		0.83	own calculations

Table A.2
PV power plant and AA-CAES operations & maintenance costs, construction time, plant size and lifetime

	PV c-Si		PV CdTe		Source
	2010	2020	2010	2020	
Operations & maintenance costs					
PV plant (excl. storage), share of investment cost p.a.	1.5%	1.5%	1.5%	1.5%	EPIA (2010b)
AA-CAES O&M fixed, EUR/kW$_{net}$ p.a.	12	12	12	12	Gatzen (2005)
AA-CAES variable, EUR cents/kWh	0.56	0.56	0.56	0.56	Mason et al. (2008)
Inflation of O&M cost p.a.	2.1%	2.1%	2.1%	2.1%	Eurostat (2010)
Construction time					
PV power plant, months	6	6	6	6	own assumptions
CAES plant, months	24	24	24	24	own assumptions
Plant size, MW$_{net}$	50	300	50	300	own assumptions
Plant lifetime, years	25	25	25	25	EPIA (2010b)

Table A.3:
PV – solar-to-electric efficiency

	PV c-Si		PV CdTe		Source
	2010	2020	2010	2020	
Module efficiency	14.0%	19.0%	11.2%	15.0%	First Solar (2009, 2010b), Suntech Power (2011), EPIA (2004)
Performance Ratio excl. temperature effect	85.0%	85.0%	85.0%	85.0%	Haase and Podewils (2011)
Temperature derate factor					
US	91.1%	91.1%	94.1%	94.1%	U.S. DOE (2011), own calculations
Spain	92.4%	92.4%	95.0%	95.0%	U.S. DOE (2011), own calculations
Germany	97.8%	97.8%	98.6%	98.6%	U.S. DOE (2011), own calculations
China	97.3%	97.3%	98.3%	98.3%	U.S. DOE (2011), own calculations
Egypt	89.0%	89.0%	92.8%	92.8%	U.S. DOE (2011), own calculations
Solar-to-electric efficiency excl. storage					
US	10.8%	14.7%	9.0%	12.0%	own calculations
Spain	11.0%	14.9%	9.0%	12.1%	own calculations
Germany	11.6%	15.8%	9.4%	12.6%	own calculations
China	11.6%	15.7%	9.4%	12.5%	own calculations
Egypt	10.6%	14.4%	8.8%	11.8%	own calculations
Module degradation p.a.	0.5%	0.5%	0.5%	0.5%	Jordan et al. (2010)
AA-CAES round cycle efficiency		70.0%		70.0%	RWE (2010)
Share electricity via storage to grid					
US		23.6%		23.2%	U.S. DOE (2011), own calculations
Spain		16.8%		16.3%	U.S. DOE (2011), own calculations
Germany		23.8%		23.9%	U.S. DOE (2011), own calculations
China		14.9%		13.9%	U.S. DOE (2011), own calculations
Egypt		33.4%		31.7%	U.S. DOE (2011), own calculations
Solar-to-electric efficiency incl. AA-CAES					
US		13.7%		11.2%	own calculations
Spain		14.2%		11.5%	own calculations
Germany		14.7%		11.7%	own calculations
China		15.0%		12.0%	own calculations
Egypt		12.9%		10.7%	own calculations

Table A.4:
Global solar irradiation, fixed tilt at optimal angle, kWh/sqm

	PV c-Si		**PV CdTe**		**Source**
	2010	**2020**	**2010**	**2020**	
US	2337	2337	2337	2337	U.S. DOE (2011), own calculations
Spain,	1951	1951	1951	1951	U.S. DOE (2011), own calculations
Germany	1180	1180	1180	1180	U.S. DOE (2011), own calculations
China	1960	1960	1960	1960	U.S. DOE (2011), own calculations
Egypt	2401	2401	2401	2401	U.S. DOE (2011), own calculations

Appendix B

Table B.1

Investment costs CSP parabolic trough

	2010	2020, excl. storage	2020, incl. storage	Source
Total Investment cost, EUR/kW$_{net}$				
US	3090	1909	3200	sum of components below
Spain, China	3313	2045	3468	sum of components below
Egypt	3090	1909	3468	sum of components below
Size of solar field, aperture area, sqm/kW$_{net}$				
US	5.6	4.6	8.6	NREL (2010), own calculations
Spain, China	6.3	5.1	9.9	NREL (2010), own calculations
Egypt	5.6	4.6	9.9	NREL (2010), own calculations
Solar field cost, EUR/sqm	211	155	155	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Solar field cost, EUR/kW$_{net}$				
US	1181	713	1338	own calculations
Spain, China	1318	795	1539	own calculations
Egypt	1181	713	1539	own calculations
Heat transfer fluid cycle, EUR/kW$_{net}$				
US	370	217	331	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Spain, China	412	241	379	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Egypt	370	217	379	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Civil work, EUR/kW$_{net}$				
US	123	63	93	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Spain, China	136	70	106	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Egypt	123	63	106	NREL (2010), Trieb (2009), Estela (2010) own calcualtions
Land costs, EUR/kW$_{net}$				
US	43	56	68	NREL (2010), own calculations
Spain, China	48	62	78	NREL (2010), own calculations
Egypt	43	56	78	NREL (2010), own calculations
Power block, EUR/kW$_{net}$	861	601	601	NREL (2010), own assumptions & calculations
6 hours Thermal Energy Storage, EUR/kW$_{net}$			593	NREL (2010), Price et al. (2002), own assumptions & calculations
Engineering, construction management, commissioning[a]	3.8%	3.8%	3.8%	NREL (2010)
Project development fixed, million EUR	10	12	12	NREL (2010)
Project development variable[a]	1.0%	1.0%	1.0%	NREL (2010)
Engineering, Procurement and Construction (EPC), EBIT-margin	8.0%	8.0%	8.0%	own assumptions

a Share of direct investment costs (solar field, heat transfer fluid cycle, civil work, power block and thermal energy storage)

Table B.2

CSP parabolic trough – operations & maintenance costs, construction time, plant size and lifetime

	2010	2020, excl. storage	2020, incl. storage	Source
Operations & maintenance cost				
Share of investment cost p.a.	2.0%	2.0%	2.0%	European Commission (2007)
Inflation of O&M cost p.a.	2.1%	2.1%	2.1%	Eurostat (2010)
Construction time, months	24	24	24	own assumptions
Plant size, MW_{net}	50	300	300	own assumptions
Plant lifetime, years	25	25	25	EPIA (2010b)

Table B.3

CSP parabolic trough – solar-to-electric efficiency

	2010	2020, excl. storage	2020, incl. storage	Source
US	14.8%	19.0%	19.0%	NREL (2010), Ferrostaal (2009), own calculations
Spain	13.6%	17.5%	17.5%	NREL (2010), Ferrostaal (2009), own calculations
China	13.3%	16.5%	16.5%	NREL (2010), Ferrostaal (2009), own calculations
Egypt	15.2%	19.3%	19.3%	NREL (2010), Ferrostaal (2009), own calculations

Table B.4

Direct normal irradiation, kWh/sqm

	2010	2020, excl. storage	2020, incl. storage	Source
US (Daggett Barstow)	2723	2723	2723	U.S. DOE (2011), own calculations
Spain (Sevilla)	2090	2090	2090	U.S. DOE (2011), own calculations
China (Erenhot)	2222	2222	2222	U.S. DOE (2011), own calculations
Egypt (El Kharga)	2578	2578	2578	U.S. DOE (2011), own calculations

Appendix C

Table C.1

Natural gas and CO_2 prices

	2010	2015	2020	2025	2030	2035	2040	2045	Source
Natural gas price, EUR/MWh$_{th}$									
US low case	11.2	19.3	24.5	30.2	35.4	40.6	46.5	53.2	IEA (2010d)
US high case	11.2	19.3	25.1	31.6	39.2	46.9	56.0	66.9	IEA (2010d)
Europe low case	19.5	28.7	32.5	36.4	41.1	46.0	51.5	57.7	IEA (2010d)
Europe high case	19.6	29.5	37.1	43.8	52.4	60.2	69.2	79.6	IEA (2010d)
CO2 price, EUR/ t CO_2									
High case	12.9	16.8	22.0	29.7	40.0	54.1	73.0	98.5	Bloomberg New Energy Finance (2011)
Low case	0	0	0	0	0	0	0	0	Own assumptions

Table C.2

Key parameters of CCGT power plant

	2010	2020	Source
Investment costs, EUR/kW$_{net}$ installed	700	700	European Commission (2008)
O&M cost excluding fuel, EUR/kW$_{net}$ installed p.a.	29	36	European Commission (2008)
System efficiency (lower heating value)	58%	61%	McKinsey & Company (2007)
Construction time, years	2	2	Own assumptions
Plant lifetime, years	25	25	Own assumptions

Appendix D

Table D.1:

Nominal discount rates for PV and CSP power plants

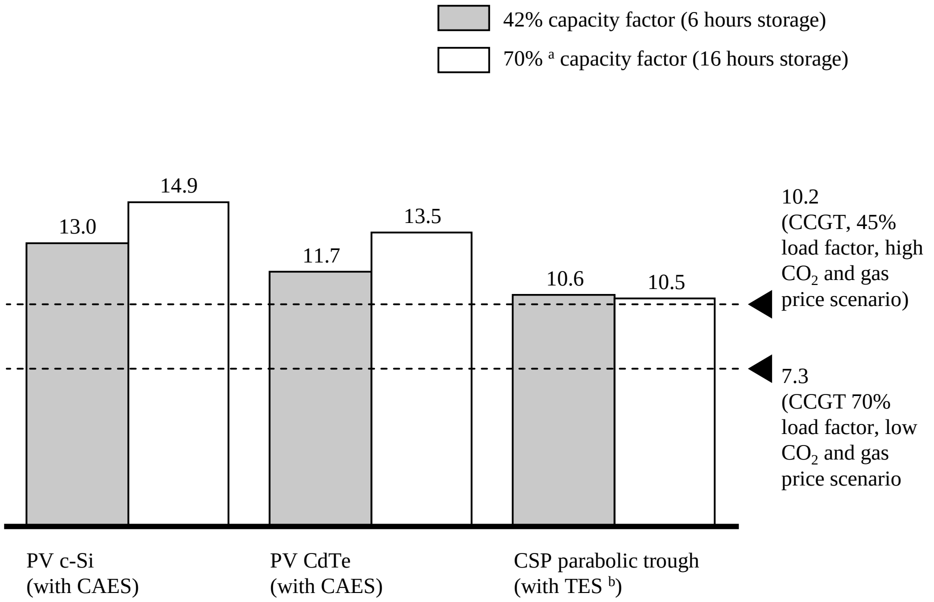
	2010	2020	Source
US	8.0%	8.0%	Own assumptions
Spain	8.0%	8.0%	Own assumptions
China	12.6%	12.6%	(UNFCCC, 2010)
Egypt	14.1%	14.1%	(UNFCCC, 2010)

Table D.2

Inflation rate and USD/EUR exchange rate

	2010	2020	Source
Inflation rate, p.a.	2.1%	2.1%	Eurostat (2010)
USD/EUR exchange rate	1.40	1.40	own assumptions

Appendix E



a In Daggett (USA), baseload electricity (85% capacity factor) could only be reached with a very large solar field, which would lead to a significant increase in LCOE. Only CSP plants closer to the equator with limited seasonal fluctuations and limited cloud cover could generate base load electricity (85% capacity factor) at no or limited additional LCOE.

b Thermal energy storage.

Fig. E.1. Levelized cost of electricity in Daggett (USA), 2020, EUR_{2020} cents/kWh

Annex I

Paper 3

Japan’s post-Fukushima Challenge - Implications from the German Experience on Renewable Energy Policy

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- Viewpoint, under review for Energy Policy -

Abtract

The Japanese electricity sector is facing serious challenges in the aftermath of the Fukushima nuclear disaster. The odds are that the government will respond to the crisis with a new Feed-in-Tariff promoting increased utilization of renewable energy. We liken the transition implied by recently updated goals for the diffusion of Renewables to the transition in Germany in the last decade. We argue that some of the lessons learned in Germany might prove valuable for the steps Japan considers taking. In particular, we highlight the importance of paying attention to both economic and environmental policy objectives. We conclude by proposing a research agenda, which includes general as well as Japan-specific issues.

Keywords: Renewable Energy, Nuclear Energy, Demand-side Policy, Feed-in-Tariff, Photovoltaic, Japan, Germany

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1. The Japanese Energy Crisis after Fukushima

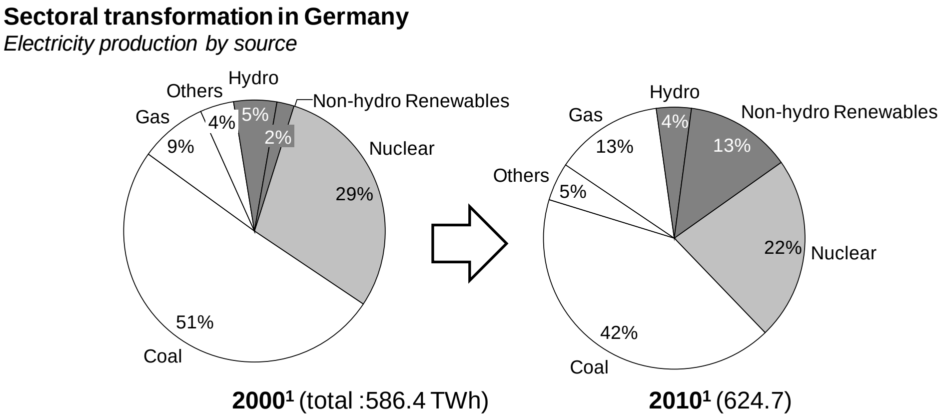
On March 11, 2011, a 9.0 magnitude earthquake struck off the coast of Japan's Tōhoku region, followed by a tsunami that caused a nuclear disaster at the Fukushima Dai-ichi power plant. The accident at the 4.7 GW nuclear facility and the continued struggle to contain radiation at the site have plunged the country's energy sector into a massive crisis, with social and economic repercussions that are likely to alter the paradigms of Japan's energy policy: In June 2011, the government proposed to review the country's 'Basic Energy Plan', from a blank state. The current draft, adopted in 2010, targeted the share of nuclear power to surge from roughly 30 % to 50 % by 2030 – a goal that seems unthinkable now, in view of the need to find communities willing to accept new nuclear reactors in their vicinity and a significant share of Japan's remaining nuclear capacity being scheduled to retire over the coming two decades (Iida, 2011). Recent polls indicate the majority of Japanese to oppose the continued use of nuclear energy (e.g., Asahi Shimbun, 2011/05/27), and Prime Minister Naoto Kan, on July 30th, proposed a nuclear phase-out until 2050.

The Fukushima meltdown might thus represent a major turning point for Japan's energy future, in that the re-orientation of policy objectives in the coming years will set the course regarding safety, energy security, costs, and carbon emissions. In this viewpoint, we aim at exploring how to mitigate some of the challenges Japan faces if renewable energy is to become a significant part of the solution. To do so, we first look at situation of Renewables in Japan; then we describe some of the lessons learned from the diffusion of Renewables in Germany and outline their implications in the context of the energy policy in Japan. We conclude by outlining a policy instrument adapted to the Japanese context and a research agenda.

2. A New Policy Approach Emerging in Response to the Crisis

Lacking significant domestic fossil fuel resources, Japanese energy policy has always been dominated by concerns of energy security (Bobrow and Kudrle, 1987; Toichi, 2003). Since the 1990s, the government increasingly focused on nuclear power as a clean, cheap, and quasi-indigenous power source, making it the central part of its strategy to fulfill carbon emission goals obliged by the Kyoto protocol. By contrast, efforts to increase the share of renewable energy sources have so far been rather limited; despite policy support in form of investment subsidies (since the mid-1990s) and a Renewable Portfolio Standard (RPS, since 2003), solar Photovoltaics (PV) and wind power accounted for only 0.21 % and 0.24 % of electricity production in 2008 (IEA, 2010a). Some geothermal capacity has been installed in the 1970s and 1990s (533 MW in total), but growth has slowed to nil since 1999 (Sugino and Akeno, 2010).

The rather bleak outlook for Renewables in Japan is about to change, however. The Fukushima accident is likely to boost public and policy support for Renewables, in that it highlights the merits of decentralized and safe energy supply. Not only has a substantial part of Japan's fossil, centralized electric capacity been forced to shut down in the aftermath of the earthquake, the public is also growing increasingly distrustful of the filthy nexus of monopolistic utilities and bureaucracies supposed to ensure the safety of nuclear power plants. While an increased use of natural gas appears the most obvious consequence of the crisis, and conservatives centered on business federation, Keidanren, even argue for revitalizing coal fired power plants, plans to increase renewable energy utilization have regained momentum as well: the government indicated a plan aiming to increase their contribution to power supply to 20 % by 2020. This is a share that even ambitious plans did not envisage before 2030.


Sectoral transformation in Germany
Electricity production by source

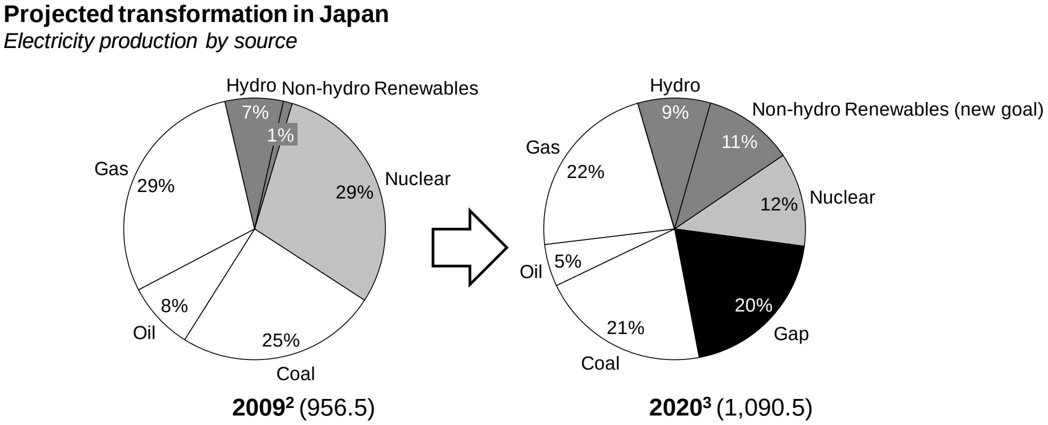

Projected transformation in Japan
Electricity production by source

Figure 1: Comparison of German energy sector transformation in 2000-2010 with challenges faced by Japan in period 2009-2019; ¹data from BMWi (2011); ² data from FEPC (2011); ³ data for nuclear power from projection by Iida (2011), non-hydro renewable contribution assumed to fulfill 20 % goal announced in June, 2010; other data from projection for 2019 by FEPC (2011). Note that the gap stemming from shut-down of nuclear facilities requires additional energy saving, extension of nuclear power plant life-time, or investments in fossil fuels above the business-as-usual scenario.

The growth needs to come mostly from sources other than hydropower – which currently accounts for more than 80 % of the electricity from Renewables – because of the largest part of the country's hydro potential already being exploited (IEA, 2008). In view of the crippled economy and the public funds earmarked for reconstruction in the earthquake area, it is imperative for the Japanese government to leverage private capital. To this end, the government will have to implement supportive policies in order to provide incentives for private investors and to overcome the economic and structural barriers that have impeded diffusion of Renewables in the past – and so far have prevented Japan from domestically reaching its Kyoto emission reduction target.

The diffusion of renewable energy in liberalized electricity markets is usually impeded by a combination of significant capital requirements and high regulatory and technological uncertainty. Initially introduced in the U.S. in the late 1970s, Feed-in-Tariffs (FIT) – or 'standard offer contracts' – have proven particularly suitable to mitigate this problem by guaranteeing a fixed purchase price for a specified period (often 10-20 years), and grid access for the electricity produced. In Japan, when it became apparent that the goals for renewable energy diffusion for 2010 would not be met with the RPS alone (planned were 1.35 % of electricity production), a FIT for solar PV was introduced in 2009 – which has, however, so far been restricted to electricity from residential PV systems, and rewards only surplus electricity (IEA, 2011a).The current situation has made energy policy an even more sensitive issue than usual. In June 2011, battered Prime Minister Naoto Kan offered his resignation conditional on, inter alia, the Diet passing a new Feed-in-Tariff bill which had originally been proposed shortly before the earthquake (Asahi Shimbun, 2011/07/30). Discussions are ongoing, but the bill can be expected to cover not only residential solar PV but a range of technologies, and possibly not only surplus but all electricity produced.

Passing the bill would create a regulatory situation similar to that under the German Renewable Energy Act (enacted in 2000; described in detail in Langniß et al., 2009). Indeed, the 20 %-target of the Japanese government implies a electricity sector transformation very much similar to what took place in Germany in the last decade (see Figure 1): Germany increased the share of Renewables from about 7 % of electricity production in 2000 to 17 % in 2010 (with some 43 GW of installed capacity); Japan is aiming at an increase from 8 % to 20 %, or the installation of about 70 GW (Duffield and Woodall, 2011). In the following, we will therefore outline some of the lessons learned from the diffusion of Renewables in

Germany and argue that they might prove valuable for the promotion of Renewables in Japan in the coming decade.

3. Lessons learned in Germany and their Application to the Japanese Case

The politics behind the German energy sector transformation were all but smooth. The FIT has been subject to continuous criticism, mostly concentrating on economic and industrial policy aspects (such as electricity prices, employment, and technology exports). Particularly in the case of solar PV, three interrelated legitimacy issues have fuelled a public and scientific debate about the scheme’s future (e.g., Frondel et al., 2008): (i) mounting payment commitments; (ii) a low research intensity in the industry; and (iii) rising net imports.

All three issues indicate potentially misdirected incentives in the industry. Market growth in the last 2-3 years has surpassed all expectations (the installations roughly doubled in 2009 and 2010, see Figure 1). The costs of the German FIT for PV have hence indeed grown substantial: Cumulative committed payments (over 20 years) reached more than €50bn in 2009 (see Table 1). Meanwhile, the imports of PV modules far outweigh exports (Figure 1), and German manufacturers move their production to low-wage countries (both attracted much criticism from the media). Interviews suggest that the FIT apparently incentivized German firms (mostly SMEs) to shift resources towards investments in new production capacities and away from long-term R&D (Hoppmann et al., 2011). In summary, the one-sided focus of policy support on the demand-side[1] may have incentivized deadweight effects and short-termism, rather than technical change and sustainable industry development.

It is likely that these issues will do only little to cloud the prospects of Renewables in Germany, particularly since the government announced a phase-out of nuclear power until 2022 (as a consequence of the Fukushima accident). We argue that there are reasons to believe, however, that the current situation and the idiosyncrasies of Japanese politics make it imperative for Japan’s policymakers to pay special attention to the legitimacy issues arising for the German FIT.

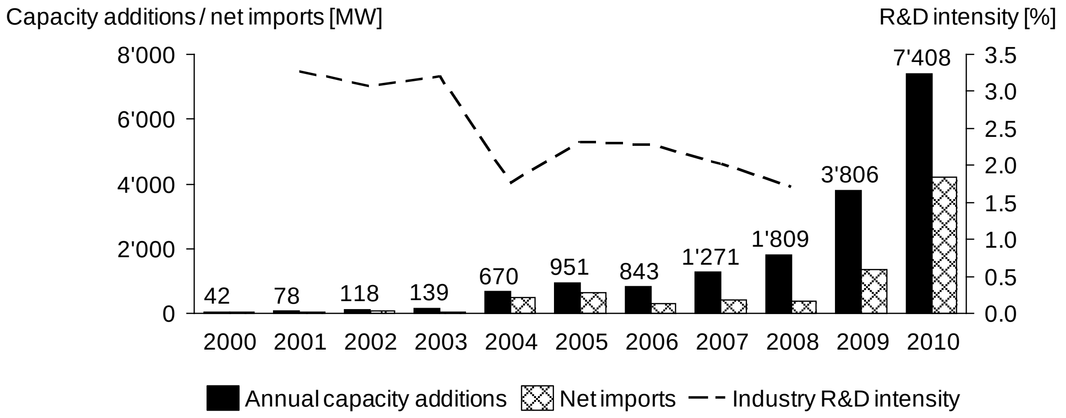


Figure 2: Main challenges for legitimacy of FIT for PV in Germany: declining research intensity in the industry and surging net imports, mainly from China. Data from the German industry association BSW-Solar (2010, 2011), which since 2011 refrains from publishing R&D data.

Table 1: Purchase price for electricity from solar PV in Germany and accruing net costs of new installations (payments committed for 20 years). Data from Frondel et al. (2010).

		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Feed-in-tariff for PV	c€/kWh	50.62	50.62	48.09	45.69	50.58	54.53	51.80	49.21	46.75	43.01
Net costs of new installations (over 20 years)	bn $€_{2007}$	0.56	0.44	0.56	0.90	1.91	6.03	7.16	8.97	8.41	17.3

One reason is that Japan will possibly rely more on the diffusion of PV than Germany does. Having long been a ‘pet project’ (DeWit, 2009) of the powerful Ministry of Economy, Trade and Industry (METI), it is very likely that solar PV will a big part of the expansion of Renewables in Japan.[2]. Recent announcements indicate that the government plans a goal of putting PV systems on 10 million roofs by 2030. (Given the sheer size of the required capacity additions and issues of grid stability, it is self-evident that other technologies, such as wind power, geothermal energy and biomass will need to play a role, too). In Germany, the solar resources are significantly lower than in Japan (3TIER, 2011), and PV accounted for only about 14 % of electricity production from non-hydro Renewables in 2010 (BMU, 2011). Another difference is the grid situation. While Japan runs an isolated island grid, Germany has the possibility to import and export electricity. In the years 2000-2008 Germany’s export-import balance of electricity (IEA, 2011b) shows an increasing net export trend.

Furthermore, there are two important differences between Japan's situation now and Germany's situation a decade ago[3]. First, responsibilities for renewable energy policy in Germany are divided between the Ministry for Economics and Technology (BMWi), often rather in opposition to "excessive" market support for Renewables, and the Ministry for Environment, Nature Conservation and Reactor Safety (BMU), which has long been supportive for environmental reasons. The balance of powers between BMU and BMWi has created a policy environment in which the legitimacy of the FIT has been based on both economic and environmental grounds, i.e. while the BMU pursues environmental interests, the BMWi aims at conformity with macroeconomic and industry political targets. This makes it difficult for vested interests from both sides of the debate to erode the policy. In Japan, on the other hand, most responsibilities in the regulation of the energy market have been concentrated in the METI.[4] Therefore, whenever plans for the energy sector and the diffusion of renewable have been drafted, they included industrial policy objectives, such as "maintaining or obtaining top-class shares of global markets for energy-related products and systems" (METI, 2010). In turn, contrasting economic objectives – such as sustaining low electricity costs for the industry – have often hindered support in the past. Some authors even speak of deliberate attempts to slow the diffusion of Renewables by pro-nuclear bureaucracies, monopolistic utilities, and lobby groups from traditional domestic industries, such as the fishing (offshore wind) and bathing (geothermal) (e.g., DeWit, 2009; DeWit and Iida, 2011). Maruyama et al. (2007:2763) second this by their rather sobering conclusion that "Japan's renewable energy policy is impeding renewable energy use rather than contributing to the spread of it". Even if such opposition is to wane in face of new political realities after Fukushima, it is very likely that paying attention to economic objectives will significantly ease the political process for whatever step Japan is about to take to support Renewables.

Second, changes in the global industry landscape might make it difficult for Japan to align economic and environmental policy objectives. Early market support and research funding in Japan in the 1980s and 90s had spurred industrial competitiveness (Watanabe et al., 2000), allowing Japanese firms to take leading positions in the global PV industry. Yet their position has eroded since then: The Japanese shares of global PV patents, solar cell production, and capacity additions fell from 51 %, 22 %, and 36 % in 1995 to 22 %, 13 %, and 7 %, respectively, in 2009 (Peters et al., 2011). The growth of the global market allowed huge production capacities to be built up, increasingly located in low-wage countries. German imports surged in the last 2-3 years with the growing presence of Chinese/Taiwanese firms, the cost advantages of which proves difficult to beat for domestic firms – and may do so for their Japanese counterparts. (And for Japan, the stakes are high: a FIT that obliges electricity customers to pay a premium for the import of Chinese solar cells would be bound to become an even more sensitive issue in Japan than it did in Germany.) Japan is still a net exporter, and the country's firms would surely regain momentum from surging domestic market support in the future. But the market has become much more competitive than it was a decade ago.

In sum, imbalanced energy policy responsibilities render economic objectives distinctively important in Japan, while changes in the global industry landscape might render these objectives distinctively difficult to fulfill. In the following, we propose an agenda for energy policy research to address these challenges.

4. A Research Agenda

Japan's situation is a salient example for a general need, faced by many developed and developing countries: to design integrated national policies that combine the economic benefits of energy or industrial policy and the environmental benefits of climate, renewable energy, or transition policy (Alkemade et al., 2011; Bazilian et al., 2010). To that end, we need to understand whether demand-side measures are on their own sufficient to incentivize significant technical change, and whether strict domestic regulation is related to positive export performance – of the regulated industry or supplying sectors. Regarding the former, theory and confirmatory evidence suggest that FIT, and other demand-side measures, do not only speed up diffusion, but also 'induce' innovation (see, for reviews, Del Río González, 2009; Jaffe et al., 2002). Regarding the latter, the literature suggests that producing sectors learn from their proximity to 'advanced users' in the home market (Beise-Zee and Rammer, 2006), especially if the market is subject to international competition (Fagerberg, 1995). Yet cases such as the Californian Wind Rush in the 1980s (supported by the world's first FIT, Nemet, 2009) and the PV FIT in Germany suggest that there are important context and technology-specific factors that influence the effects of demand-side measures. In order to derive reliable policy implications, it is indispensable to better understand these context effects.

For Japan in particular, we propose that demand-side support for PV in Japan (e.g., in form of a FIT) needs to pay attention to avoid misdirected incentives and to create a regulatory environment in which domestic firms can thrive. One option may be complementary supply side measures, such as R&D funding or dynamic standards.

For a product very similar to PV modules, liquid crystalline displays, Japan has implemented one of the most successful supply-side policy programmes, the so called ‘Top-Runner’ programme. The programme, enacted in 1998 under the supervision of the METI, is a scheme to stimulate energy efficiency for household and office appliances. It does so by iteratively setting mandatory efficiency standards (along multiple criteria) based on the most efficient products on the market and consultations with advisory committees (Kimura, 2010). (Business stakeholders, including domestic and international equipment manufacturers, are consulted in the standard-setting process). Transferring the positive experience from the Top-Runner approach to an adapted FIT for PV might be an option to create a more balanced regulation of the demand and supply sides. A modified FIT could require solar modules to fulfill a rolling, efficiency standard. For instance, the FIT could integrate a condition that has been implemented in an investment subsidy that was granted to residential systems in 2009: in order to receive the subsidy, cell conversion efficiency had to exceed the – technology-specific – average on the market (IEA, 2011a). Such an integration of aspects from the Top-Runner approach and the FIT could be a way to incentivize both diffusion and investment in long-term R&D and continuous product innovation. Further, since Japan has a well functioning innovation system in the semiconductor and solar PV industries and is a high-wage country, it can be expected that such a policy is much better suited to the capabilities of the industry than a scheme merely rewarding production at the lowest costs.

Another important aspect is how to integrate environment and economic objectives together in the complex domestic policy situation on the other hand, and how to integrate such new policy into international governance structures such as those of the UN on the other hand (Kanie, 2011). Horizontal institutional integration is indispensable in order to make a safe landing for low-carbon society in the long-run, while such question as compatibility with WTO law of such a scheme is important for vertical integration. No charges have been filed against the ‘Top-Runner’ programme so far, but in many product categories international competition is of little significance (Nordquist, 2006). How to implement a dynamic version of this standard, or how to design a committee-based standard-setting process, also requires further research. Yet a successful integration of economic and environmental benefits might turn problem-fraught Japan into a role model for renewable energy policy, as it already is in the field of energy efficiency.

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Footnotes

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[1] Market subsidies paid in 2010 amounted to about €8bn, while R&D funding was about €70m in 2009 (IEA, 2010b)

[2] A study conducted by the METI (then MITI) in 1997 revealed good potential for solar PV in Japan (Murata and Otani, 1997).

[3] For a comparison of Japan’s and German’s climate policy, which is of course very related, see the recent book by Watanabe (2011)

[4] There is an ongoing discussion as to under which government agency will the nuclear safety be reorganized. One option is under the cabinet office, while the other is under the ministry of environment.

Annex I

Paper 4

Composting Projects under the Clean Development Mechanism: Sustainable Contribution to Mitigate Climate Change

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- Published in Waste Management (2011) 31 (1): 138-146 -
doi: 10.1016/j.wasman.2010.09.007

Abstract:

The Clean Development Mechanism (CDM) of the Kyoto Protocol aims to reduce greenhouse gas emissions in developing countries and at the same time to assist these countries in sustainable development. While composting as a suitable mitigation option in the waste sector can clearly contribute to the former goal there are indications that high rents can also be achieved regarding the latter. In this article composting is compared with other CDM project types inside and outside the waste sector with regards to both project numbers and contribution to sustainable development. It is found that, despite the high number of waste projects, composting is underrepresented and a major reason for this fact is identified. Based on a multi-criteria analysis it is shown that composting has a higher potential for contribution to sustainable development than most other best in class projects. As these contributions can only be assured if certain requirements are followed, eight key obligations are presented.

Key words: Compost, Sustainable development, Clean Development Mechanism (CDM)

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1. Introduction

Currently, international negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) are trying to establish a follow-up treaty to the Kyoto Protocol, which expires in 2012 and aims at the reduction of greenhouse gases (GHG) within many sectors in both developed and developing countries (UNFCCC, 1997). Experiences form the current regime can be helpful for the design of such a post-Kyoto treaty. Thus, we want to shed light on one aspect, namely waste treatment and, more specifically, composting under the Kyoto Protocol's Clean Development Mechanism (CDM), which addresses climate change mitigation in developing countries. The Intergovernmental Panel on Climate Change (IPCC) considers waste as one of the seven key sectors contributing to climate change (IPCC, 2007). The proposed corresponding mitigation technologies by the IPCC focus either on landfill gas recovery or on the prevention of methane generation in landfills either by means of aeration or avoidance of landfilling (e.g. via composting). These strategies are already being applied at large scale in developed countries. For instance, the European Union with its 1999 landfill directive which promotes incineration, composting and bio-methanisation of waste (European Community, 1999) managed to reduce landfill emissions significantly (U.S. EPA, 2006). While the OECD is projected to decrease its landfill emissions by 31% in 2020 compared to 1990 levels, developing countries are expected to generate more waste and in the same period of time contribute to a 7 % increase in total global landfill gas emissions reaching 817 MtCO$_2$eq in 2020. Fast growing populations and personal incomes as well as expanding industrialization result in increasing waste production in developing countries (U.S. EPA, 2006). Local authorities (especially in the cities) often do not cope with the challenging task of providing a proper waste management service (UNEP, 2005). This can lead to the contamination of streets and drinking water and, consequently, to severe threats to health particularly for the poorer population. Changing open dumpsites into sanitary landfills is a frequent approach to solving these problems. However, if the landfill is neither aerated nor equipped with gas capture systems, the GHG emissions will actually increase compared to an open dumpsite. Barton et al. (2008) compared different emission reduction options in this sector specifically for developing countries. In their study the landfill gas flaring and landfill gas to power scenarios reduced GHG emissions considerably, but composting and anaerobic digestion resulted in options being carbon neutral or negative. Bearing in mind its relatively simple technology, the authors propose composting to be the first process to be considered when replacing open dumping. The high percentage of biodegradables in waste in developing countries, the low labour costs and the relative simple and inexpensive, but labour intensive technology are the main reasons why composting is also considered by other authors as being a particularly favourable waste management system in developing countries (Barton et al., 2008; Elango et al., 2009; Gonzenbach and Coad, 2007; Hofny-Collins, 2006).

The Clean Development Mechanism aims to reduce emissions in developing countries (so-called non-Annex-1 countries of the Kyoto Protocol). The mechanism is project-based and issues certified emission reduction warrants (CERs), which can be used in developed countries (so-called Annex-1 countries) to comply with emission reduction targets. The CDM has a twofold objective. First, it supports developed countries in reaching their emission reduction targets through the mobilisation of more cost efficient reduction options in developing countries, where, second, the emission reduction projects shall contribute to sustainable development (UNFCCC, 1997). Amongst others, the waste sector is a target of investors in emission reduction projects under the CDM (Fenhann, 2010). Regarding the second objective of the CDM, Sutter and Parreño (2007) published a study in which by far not all of the assessed CDM projects contributed significantly to sustainable development. Furthermore, the fact that CDM does not offer adequate incentives for the achievement of the second goal in the host countries has led to criticism (Olsen, 2007). A shift within the business-sustainability trade-off in favour of the second objective only happens when value is attributed to sustainability e.g. by awarding labels such as the Gold Standard, the most prominent high quality credit label. It rewards outstanding CDM Projects in terms of their contribution to sustainable development leading to a higher market price for certificates. Though there are indications that composting is able to deliver high rents of sustainability in developing countries (e.g. Gonzenbach and Coad, 2007; Zurbruegg et al., 2005) composting projects are currently not eligible for the Gold Standard (Gold-Standard, 2010).

To our knowledge there is no study comparing composting with alternative waste management projects or even other sector projects under the CDM framework regarding both project numbers and contribution to sustainable development. The present article studies the current state of composting projects under the CDM in Section 2, and assesses their contribution to sustainable development by comparing it with Gold Standard labelled projects of different types in Section 3. Based on this assessment, literature, and expert interviews, the article presents eight sustainability requirements for composting projects in developing countries, and concludes with some recommendations in Section 4.

2. The situation of composting projects under the CDM

2.1. Number of projects

Thus far, the CDM has generated several types of mitigation activities whose shares in terms of project numbers are shown in Figure 1. In March 2010, over 50% of the 2062 projects which were registered at the UNFCCC as CDM activities (Fenhann, 2010) were based on renewable energy and one quarter on methane avoidance (e.g. solid waste or animal waste and waste water) with almost 9% stemming from solid waste management. This share appears to be rather high compared to the global contribution to anthropogenic greenhouse gas emissions of the waste sector of 2.8% (IPCC, 2007). With 154 projects (6.6% of the total registered activities), landfill gas projects[1] (LFG) are by far the biggest contributor. In fact, landfill gas projects were among the first projects registered by the UNFCCC (UNFCCC, 2010) and many big dump-sites around the world have been "cleaned" thanks to the incentives created by the CDM. These are mainly based on revenues from methane destruction which make the projects financially very attractive, as recently shown by Schneider et al. (2010).

On the contrary, the number of composting projects is much smaller (37) though as mentioned above they are well suited for implementation in developing countries. The first composting project under the Clean Development Mechanism was accepted in 2006 (Barton et al., 2008) but only a few followed after that. By today, none of the 37 registered projects – 12 being based on municipal solid waste (MSW) and 25 on agri-waste – managed to issue credits, yet.

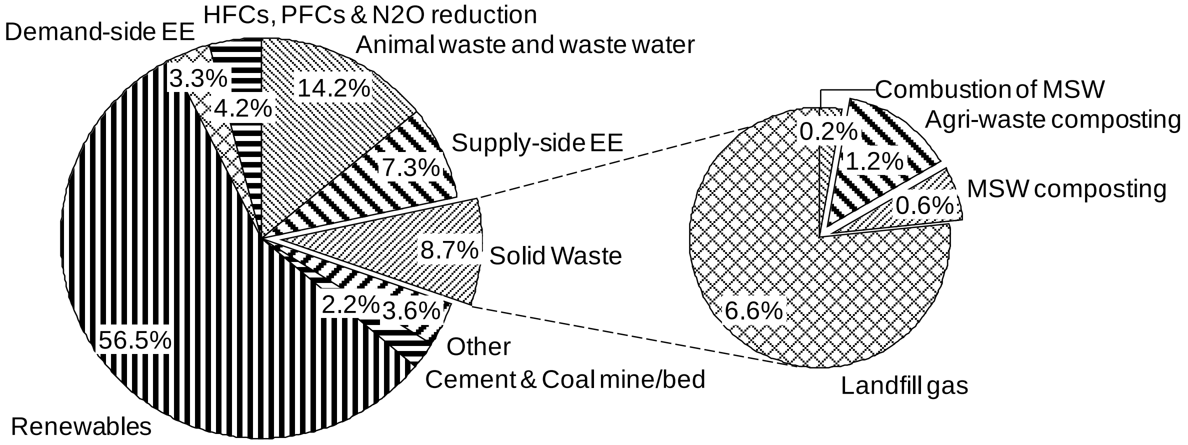

Figure 1. Number of projects (in %) of each project category with special focus on solid waste (based on Fenhann, 2010)
(EE = Energy Efficiency, HFCs = Hydrofluorocarbons, PFCs = Perfluorocarbons, N2O= Nitrous Oxide, MSW = Municipal Solid Waste)

Though, according to Barton (2008) composting leads to higher emission reductions, most investors seem to prefer landfill gas projects. This might seem surprising but can be explained to a great extent by the methodologies for the calculation of the GHG emission reductions.

2.2. Methodologies for the calculation of the emission reductions

All methodologies that deal with solid waste refer to the same UNFCCC tool[2], which uses a first order decay model to calculate the baseline methane emissions, i.e. the quantity of methane that would have

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[1] LFG flaring and LFG to energy

[2] Methane tool of the UNFCCC (2006)

been emitted to the atmosphere in the absence of the CDM project[3]. Originally designed to assess GHG emissions from landfills (IPCC, 2006) this model is now used in all methodologies related to solid waste management. It distinguishes between different climatic circumstances, particular waste types, and landfill management practices. Each waste type is characterized by its degradation velocity and its degradable organic carbon content. According to this model, methane emissions that would have been emitted in year y from a quantity of waste dumped in year x is proportional to $e^{-k(y-x)}$ where k is degradation velocity of the waste. Each year the methane emissions decreases according to this first order decay law and the higher the degradation velocity, the greater the slope of the methane emission curve.

In Figure 2, we present the typical profile of the methane emission curve calculated as by the UNFCCC tool for a dump site where a supposed constant quantity of waste is being accumulated for 10 years, the typical CDM project duration. The curve represents the sum of the 10 different first-order decay curves from waste treated in year 1 to 10 (every shade in Figure 2 represents the amount of methane generated annually from waste disposed in one single year) and has a typical shape that we can split into two parts. First, the raising phase where the methane emissions ramp up before reaching a maximum after 10 years (to the left of the dotted line) and the decreasing phase where in the absence of fresh waste the methane emissions decrease according to the first order decay law (to the right of the dotted line).

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[3] A project’s emission reductions are calculated by the subtraction of the project emissions (i.e. the emissions that occur due to a project) from the baseline emissions. (UNFCCC, 2010)

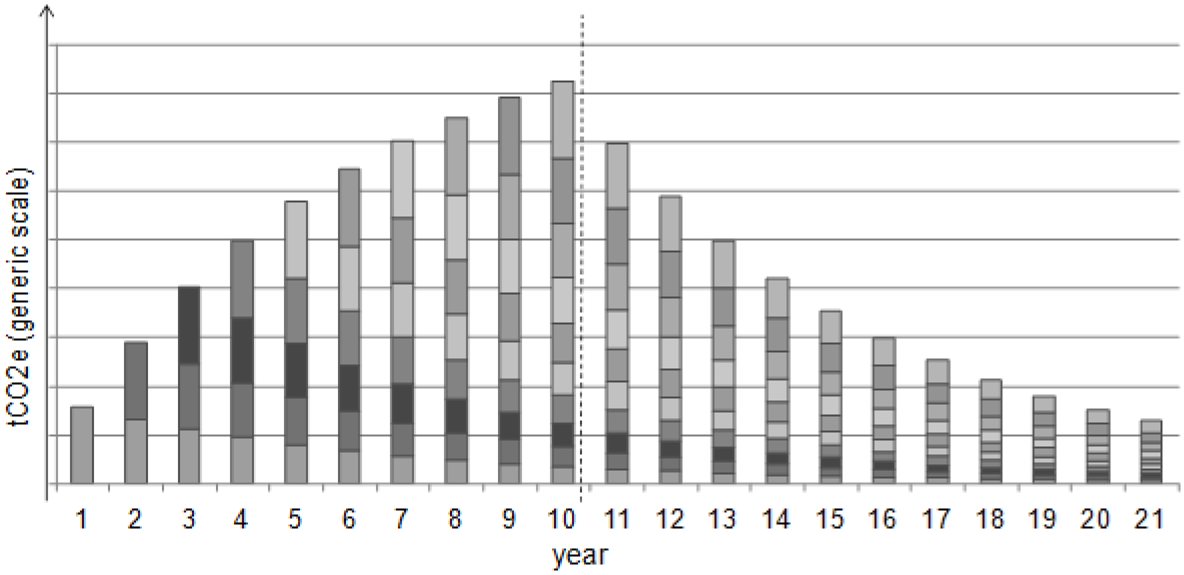

Figure 2. Methane baseline of a 10 year stream of waste calculated according to the UNFCCC (2010) tool[4]

Despite the fact that both composting and landfill CDM projects use the same tool, there is a fundamental difference between the two project types. In the case of composting, methane emissions which would have occurred in the following years are avoided, i.e. the actual emission reductions of a composting project lasting ten years would contain all emissions shown in Figure 2 and even those beyond the year 21. In landfill gas projects the methane destruction only starts after the landfill has been closed and covered (i.e. in year eleven). Therefore only the emissions to the right of the dotted line are avoided. However, according to the methodology, a composting project lasting ten years will only be rewarded for the rising part of the curve, a landfill project for the decreasing one. This has an important influence on the flow of CERs and therefore on the contribution of the CDM to financing these activities. Indeed, for composting projects most emission reductions occur close to the end of the crediting period while during the first few years of the crediting period the methane baseline emissions are very low. This translates into low cash flows in the early stages, and higher ones in the later stages of a project. Underlying an interest rate on investments, this has a negative impact on a project's profitability as early revenues are discounted to a lesser extent than late ones when calculating the net present value (NPV) of investments (Brealey and Myers, 2000). This issue is even more critical now in a market where there is no clear post-2012 visibility for CDM. Moreover, if the project emissions (due to energy use in operating the composting plants) are subtracted from the baseline emissions, the resulting emission reductions from the project can be zero or even negative in the early phase. These constellations can prevent project developers from considering composting options under the CDM since such projects are not as profitable, or could even appear as a non-mitigating activity. In turn,

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[4] The degradation velocity is based on "Garden, yard and park waste" for tropical wet climate and is equal to 0.17 y^{-1} which is the maximum value for this type of waste.

landfill projects profit from high cash flows early on which make them financially attractive. Besides this methodological issue CDM composting projects clearly face other barriers which are, by contrast, inherent and not imposed by climate policy. The complexity of waste separation might be one of these barriers. This may explain why projects dealing with purely organic residues in agribusiness are more frequent than those dealing with MSW.

From a mitigation point of view, the situation is therefore a paradox: Though composting leads to the immediate avoidance of nearly all methane emissions, the monetary rewards are discounted and delayed. This was recently also criticised by a study on the CDM methodologies applicable to the waste sector (Müller et al., 2009). On the other hand, landfill projects, where GHGs are emitted until the landfill closure, benefit from a decisive incentive from the CDM. These facts explain to a large extent the LFG projects' high investment attractiveness in comparison to composting projects and the difference in terms of project numbers, respectively.

3. Contributions to Sustainability

3.1. The triple bottom line of sustainability

As the CDM aims to not only reduce emissions but also to "assist Parties not included in Annex-I in achieving sustainable development" (UNFCCC, 1997, p.11), we now want to elaborate on this second goal. In order to move towards sustainability a consensus of three different interests, namely economic, social, and natural capital must be achieved (United Nations General Assembley, 2005). This so-called "triple-bottom-line of sustainability" should also be applied to the waste sector (den Boer et al., 2007; Morrissey and Browne, 2004) and thus will serve as foundation for the following chapter.

3.2. How to measure the sustainability contribution of CDM projects

While the GHG-emission reductions by CDM projects are calculated according to the methodologies provided by the UNFCCC, there is no comparable official regulation for measuring their contribution to sustainable development (Olsen, 2007). Several initiatives by researchers and labelling organisations have addressed this shortcoming by developing respective assessment methodologies in order to give more value to the second objective of the CDM.

The Gold Standard is the most prominent quality credit label for GHG-mitigation projects. Initiated by the World Wide Found for Nature (WWF), the Gold Standard today is supported by more than 60 NGOs worldwide. The Label awards outstanding projects in terms of their contribution to sustainable development. To achieve Gold Standard certification, CDM projects, as well as projects providing certificates for the voluntary market, have to fulfil the Gold Standard eligibility criteria, which exclude all project types other than renewable energy supply or energy efficiency. Furthermore, the evaluation includes an environmental impact assessment, a stakeholder consultation and a sustainability assessment. The latter comprises a set of twelve sustainability criteria (four for each sustainability dimension) assessed with the help of descriptive five-step scales (Gold-Standard, 2010). The assessment and its criteria stem from the methodology Multi-Attributive Assessment of CDM (MATA-CDM) which is based on the Multi Attributive Utility Theory. It has been developed by Sutter (2003) and is structured along the five step identification of sustainability criteria, defining indicators and their utility function, weighting the criteria, assessing the projects, and aggregating and interpreting the results. The twelve sustainability criteria identified in Sutter’s study differ only slightly from the Gold Standard criteria and have been used in other studies to assess sustainability rents of CDM projects (Heuberger et al., 2007; Nussbaumer, 2009; Sutter and Parreño, 2007).

The present study uses the simplified MATA-CDM, as described by Nussbaumer (2009)[5] dealing with the standardized Project Design Documents (PDD) for CDM projects as single source of information. One researcher assessed all projects in order to guarantee that one single standard for assessment was applied. The scores of each project on each dimension were then discussed among the three authors and partly corrected.

3.3. Comparing composting projects with other best-in-class projects

In total, twenty-seven CDM projects were compared in this study regarding the twelve sustainability criteria. The projects are split into eight different project types according to Table 1. All assessed projects are labelled as Gold Standard (GS) projects or have applied for GS-registration except the composting projects as they are not eligible for the GS. GS projects tend to show higher sustainability rents than comparable non-GS projects (Nussbaumer, 2009) and therefore serve as stricter benchmark for composting projects.

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[5] For details on this methodology please refer to his study. Due to the lack of respective data, the scoring function for the criteria fossil energy resources has been modified, resulting in the criteria being qualitative.

Table 1: Assessed projects

Project type Abbreviations	Project type	Gold Standard	Number of assessed projects
Compost-M	Composting of municipal solid waste	Not eligible	5
Compost-A	Composting residues from agribusiness	Not eligible	5
GS-Landfill	Landfill gas to power	Labelled or applied for registration	3
GS-Biogas	Biogas to power	Labelled or applied for registration	3
GS-Biomass	Agricultural biomass to energy	Labelled or applied for registration	3
GS-Household	Energy efficiency on the household level	Labelled or applied for registration	3
GS-Solar	Solar cooking	Labelled or applied for registration	2
GS-Wind	Wind farm	Labelled or applied for registration	3

Sustainable development profiles of different CDM project types

For the comparison criteria by criteria, the study reverts to the amoeba graphs[6] described by Nussbaumer (2009). The specific sustainable development profiles of the 8 assessed project types are presented in Figures 3 and 4. To facilitate the reading of the figures, the 12 criteria and their positions in the graph are presented in Table 2.

Table 2: Sustainability criteria

Abbreviation	Criteria	Position in the amoeba graph
SOC1	Stakeholder participation	12 o’clock
SOC2	Improved service availability	1 o’clock
SOC3	Equal distribution of the CER revenues	2 o’clock
SOC4	Human capacity development	3 o’clock
ENV1	Fossil energy resources	4 o’clock
ENV2	Air quality	5 o’clock
ENV3	Water quality	6 o’clock
ENV4	Land resource	7 o’clock
ECO1	Regional economy	8 o’clock
ECO2	Microeconomic efficiency	9 o’clock
ECO3	Employment generation	10 o’clock
ECO4	Sustainable technology transfer	11 o’clock

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[6] The 12 criteria with their scale from -1 to 1 are spanned in a circle similar to a clock face and where the scores by each project type define a characteristic sustainability profile. The resulting line represents the average of all projects which have been assessed per project type.

In our study we delineate two different types of composting projects, i.e. whether municipal solid waste (hereafter referred to as compost-M) or agricultural residuals (Compost-A) are composted. This delineation is based on the expectation that the two types might significantly differ regarding their sustainability contribution as they are based on very different waste and value chains. When looking at the results (Figures 3a and b), this expectation is confirmed. Compost-A projects achieve lower ratings regarding improved service availability, water quality, regional economy, and employment generation due to the following reasons. Firstly, while MSW-composting in the assessed cases improves waste management service for the involved population, composting residues from agribusiness do not have a comparable influence on the availability of services. Furthermore, compost produced by agribusiness is generally used within the respective plantation whereas MSW-compost substitutes expensive chemical fertilizers and therefore is of great value for small farmers. Secondly, MSW-composting reduces water content of the municipal waste and therefore toxic leakage in landfills, which often endangers the water quality in residential neighbourhoods. This improvement in water quality has been rated higher than the prevention of eutrophication thanks to composting residues from agribusiness. Thirdly, four of the five assessed Composting-A projects are located in Malaysia, whereas the assessed Composting-M projects are located in Bangladesh, India, Colombia the Philippines, and China. The Human development index (UNDP) of these countries is clearly smaller than the one of Malaysia and thus the contribution to regional economy has been rated higher. Fourthly, the employment generation in Composting-M projects due to the collection and the sorting of the municipal waste is much higher than in Compost-A projects where only little additional labour is needed. The only criterion where Compost-A projects achieve higher ratings than Composting-M is microeconomic efficiency.

Composting projects outperform all other project types regarding the criteria land resource (Figures 3 and 4). The reasons for this high rating are the contribution of compost to carbon sequestration (Fortuna et al., 2003; Fronning et al., 2008) and, the capacity of compost to improve soil fertility in many ways. Compost for instance, is able to reduce erosion and nitrate leaching thanks to the increase in soil aggregate stability (Fuchs et al., 2008) and water holding capacity of farm land (Evanylo et al., 2008; Lima et al., 2009). Even degraded soils can be restored with the aid of compost (Cogger, 2005; Ros et al., 2003). With its content of plant nutrients such as nitrogen, phosphorus, and potassium, compost is furthermore a valuable fertilizer (Ngakou et al., 2008; Whalen et al., 2008) and thanks to its suppressive effect on plant pathogens (Abbasi et al., 2002; Hoitink and Fahy, 1986) compost has the capacity to control plant diseases. All these features account for the high rating of composting projects for the land resource criterion and are particularly important for agriculture in developing countries where crop inputs such as chemical fertilizers and pesticides are not readily available (Niggli et al., 2009).

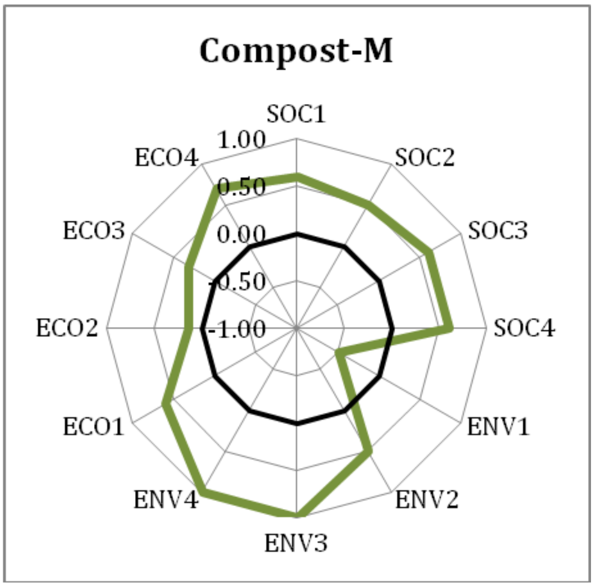

Figure 3a. Compost-M

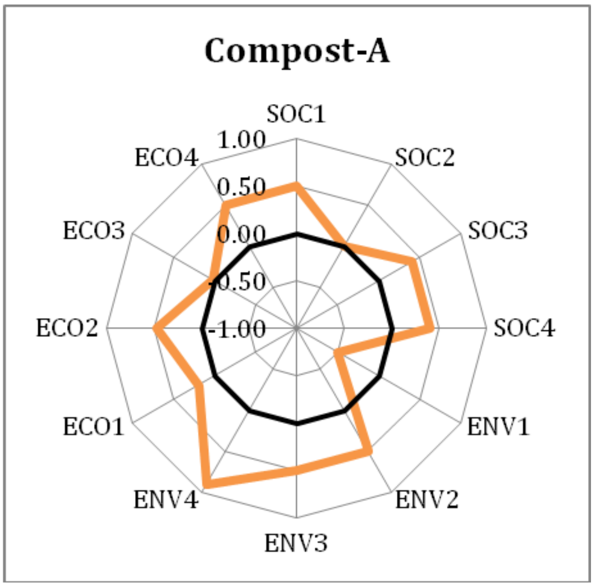

Figure 3b. Compost-A

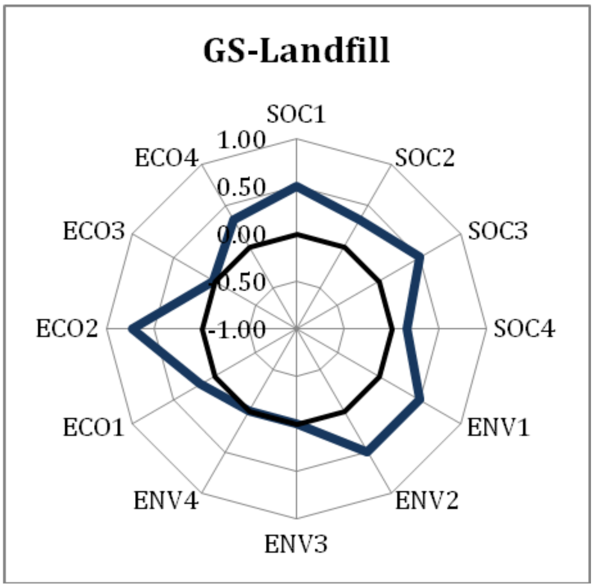

Figure 3c. GS-Landfill

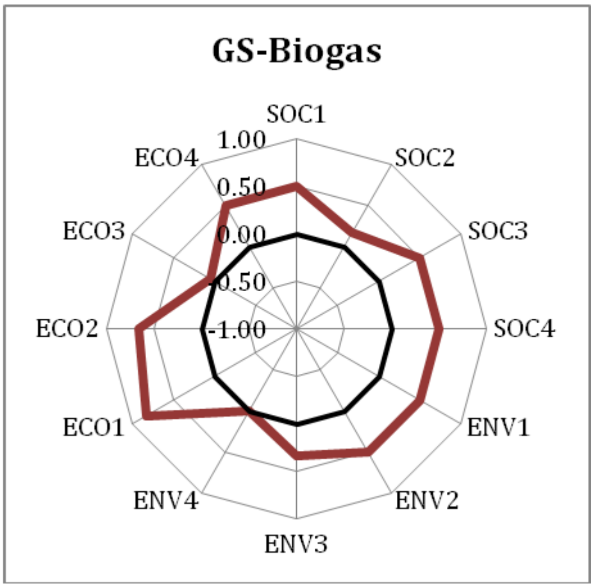

Figure 3d. GS-Biogas

Figure 3: Sustainable development profile of CDM projects related to waste or biogas

A different picture is found when comparing the project types regarding the criterion fossil energy use. While all other project types provide alternative energy and hence are able to replace fossil energy which results in a positive rating, composting projects receive a negative rating for this criterion due to the fuel consumption of transport vehicles and turning machines (Figures 3 and 4). The fact that compost is able to substitute chemical fertilizers (Ngakou et al., 2008; Whalen et al., 2008), thus reducing the fuel consumption of energy intensive fertilizer production (Kokkora et al., 2006), might change the picture but is not taken into consideration in the assessment as it lies outside the CDM project boundaries.

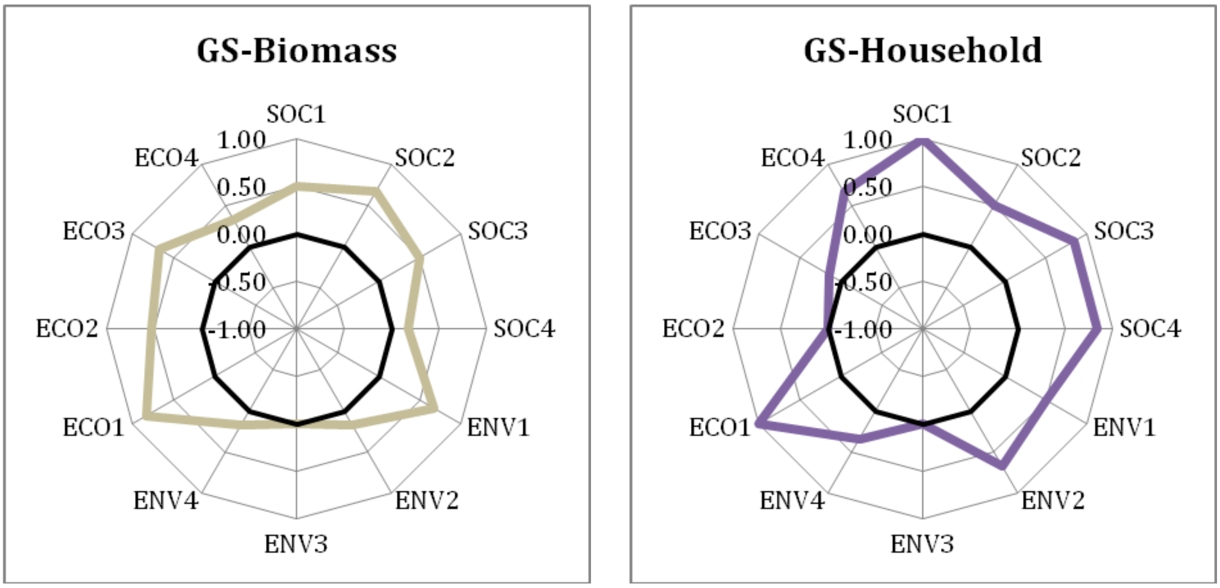

Figure 4a. GS-Biomass

Figure 4b. GS-Household

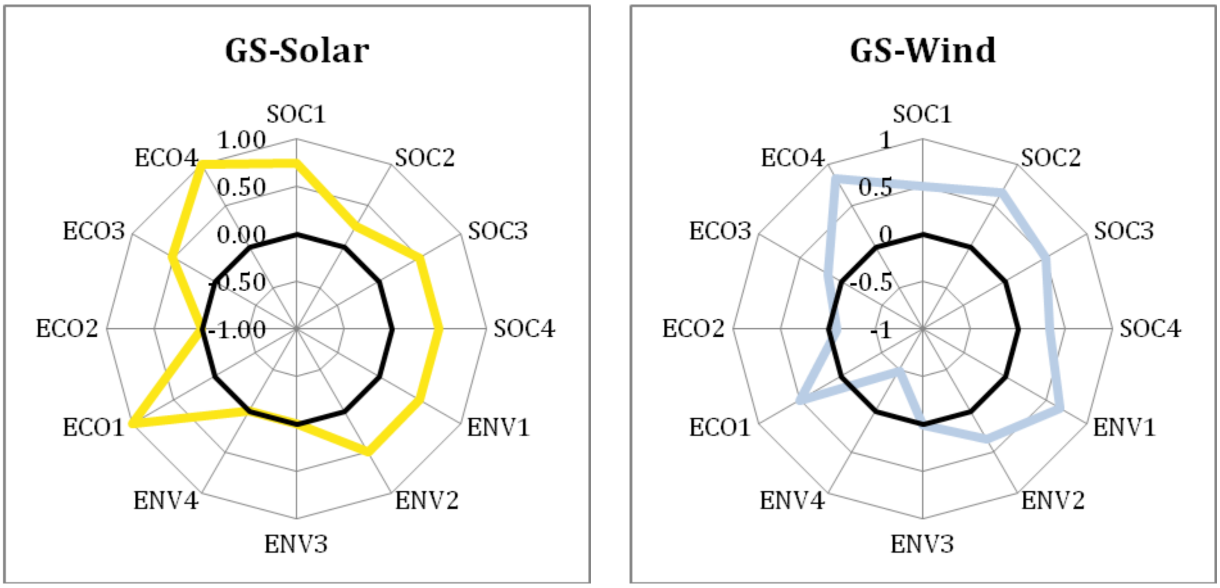

Figure 4c. GS-Solar

Figure 4d. GS-Wind

Figure 4: Sustainable development profile of CDM projects other than waste or biogas related

Aggregated contribution to sustainable development by project type

Unlike Nussbaumer (2009), the present study compares the aggregated contribution to sustainability of the different projects while being aware that this single figure only represents an imperfect value for absolute contribution to sustainable development. However, it provides a measurement for the contribution to sustainable development of the different project types on the scale from totally unsustainable (-1) to fully sustainable (+1). The average scores and respective standard deviations are shown in Figure 5 for each project type. All assessed CDM-project types contribute positively to sustainable development. The highest average score was reached by Household projects (0.54), followed by Compost of MSW, Solar Cooking, Biomass, and Biogas ranging from 0.50 to 0.42 (Figure 5). Lower scores have been attached to the project types Compost of Agricultural Leftovers (0.33), Wind (0.32) and the lowest for Landfill Gas to Power projects with a score of 0.31. The figures show clearly that composting at least keeps up with best in class of renewable energy supply or energy efficiency projects, and in case of MSW is even one of the most sustainable project types. Landfill Gas to Power is, by contrast, at the lower end of the compared project types.

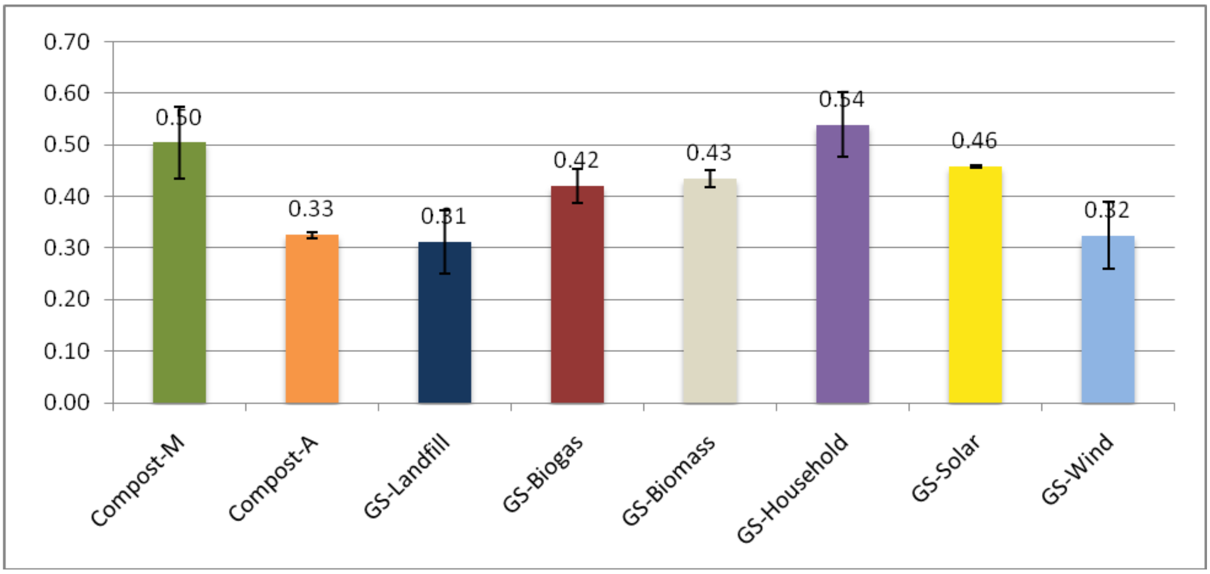

Figure 5. Sustainable development impact of CDM projects: Comparison of different project types.

3.4. How to assure high sustainability rents?

After having shown that composting project can definitely keep up with or even outperform other best-in-class project types regarding their contribution to sustainable development, this section defines the preconditions and requirements necessary to assure this contribution. For this reason, information from the sustainability assessment, different compost quality regulations, Gold Standard sustainability requirements (Gold-Standard 2010) and interviews with six experts representing different areas of specialisation such as composting in developing countries, CDM, sustainability measurements or general compost quality (see Table A in the Annex) was compiled. These interviews served to reconfirm our choice of requirements regarding their relevance, sufficiency, and the feasibility of their respective control in developing countries.

In a first step, potential negative as well as positive effects of composting projects on sustainable development were collected. Secondly, measures to prevent the negative effects as well as preconditions to support the positive effects were specified. Thirdly, the most important effects and the related requirements were prioritised, which led to the short list of eight sustainability requirements for composting projects shown in Table 3.

Table 3. Sustainability Requirements for composting projects

Requirement	Criteria	Source
Correct fermentation process	Temperature during composting process 55°C, 21 days or 65°C, 7 days	(Fuchs et al., 2004)
Limitation of heavy metals	Cadmium: < 1 mg/kg dry matter Copper: < 100 mg/kg dry matter Mercury: < 1 mg/kg dry matter Nickel: < 30 mg/kg dry matter Lead: < 120 mg/kg dry matter Zinc: < 400 mg/kg dry matter	(Fuchs et al., 2004)
Limitation of Impurities in compost	Glass, metal, plastic < 0.5% weight dry matter Stones (> 5 mm) < 5 % weight dry matter	(Fuchs et al., 2004)
Leachate control	Contamination of ground and water by leachate has to be avoided by adequate structural measures. (e.g. solid ground, roof , leachate collection system, compost-fleece)	(Duckworth, 2005)
High quality Compost is used in agriculture, horticulture, home gardens or potted plants	Project has to account for the use of the compost: It is neither dumped in landfills nor burnt	Evident criterion
Inclusion of stakeholders	Inclusion of stakeholders of the existing formal as well as of the informal waste management system, notably waste pickers, collectors and recyclers	(Gonzenbach and Coad, 2007)
Transparent statistic of project jobs including construction and maintenance of the composting plant	The number and classification of jobs in construction and maintenance of the composting plant should be declared in the PDD and monitored over the whole project period.	Criterion arisen from sustainability assessment
Clear commitment by project owner and associated agro-companies to sustainable development	For composting of palm oil residuals: compliance with the latest version of the roundtable on sustainable palm oil production For other production systems similar solutions have to be found	(Gold-Standard)

The first sustainability requirement focuses on the correct fermentation process within a composting project, which is of enormous importance for both the mitigation of methane and other GHG emissions and for the quality of the compost. If the latter is unsatisfactory, compost is not used and many positive contributions to sustainable development no longer have any effect. On the contrary, the use of bad compost could potentially result in contamination of arable land with heavy metals or impurities. That is why the proposed shortlist comprises four further requirements related to compost quality and its appropriate use, namely the limitation of (1) heavy metals and (2) impurities in compost, (3) leachate control and (4) the appropriate usage of the compost.

It is self-explanatory that a sustainable project must not disfavour marginalised and poor people. Many waste pickers or people who make their living from recycling waste may suffer under a new waste collection system. These people are important stakeholders and have to be included in the consultation process. The project should offer them alternative solutions for income generation (Gonzenbach and Coad, 2007).

In spite of the undoubted importance of employment for sustainable development, quantity and quality of jobs are often neglected in sustainability assessments of CDM projects. Because accurate figures were missing, the number of jobs generated has also in the course of the present study been difficult to evaluate. Transparent statistics regarding number and classification of generated jobs would be helpful to appraise CDM projects regarding their job creation potential. This requirement, however, is not specific for composting but also applies to all other project types.

Most projects composting residues from agribusiness are connected to the production of palm oil, which is widely used as cooking oil but has also become more and more important as a biofuel over the last 10 years. Against the background of the recent food crises, biofuel projects have generally become a bone of contention. In the case of palm oil, it is not only competition for arable land for food production that has become an issue, but also the fact that new plantations are often established on newly-cleared rain forest land (Reijnders and Huijbregts, 2008; UNDP, 2007; Wicke et al., 2008). On this account it is important to mention that all assessed projects comply with the latest standards of the roundtable on sustainable palm oil production (RSPO, 2010) as it is a precondition to receive Gold Standard certification.

4. Conclusions

The waste sector plays an important role for climate change and its mitigation in both developed and developing countries. Especially for the latter, composting seems to be a very appropriate mitigation option. The debate on a future international agreement to limit climate change can benefit from insights gained under the existing regime, i.e. the Kyoto Protocol. Hence, this article sheds light on current practice and the significance of composting within this regime’s Clean Development Mechanism which aims at GHG reductions and sustainable development in developing countries. We find that significantly fewer composting projects are implemented under the CDM than related project-types aiming at the mitigation of methane emissions from solid waste, i.e. mainly landfill gas projects which either flare the methane or use it to produce power. While these latter projects are, compared to the share of anthropogenic GHG emissions of the waste sector, clearly overrepresented, the barriers for the implementation of composting projects seem to be much higher, leading to their under-representation. The methodology for the calculation of emission mitigation was identified as one major barrier for composting projects. Originally developed for landfill gas projects, the model used in this methodology discriminates composting because the allocation of emission reduction certificates is postponed which reduces the projects' financial attractiveness considerably. In turn, landfill gas projects are treated preferentially as emission reduction warrants are not deferred.

Regarding their contribution to sustainability, our analysis shows that composting projects can compete with other best in class CDM projects. Composting projects dealing with municipal solid waste perform better than projects composting residues from agribusiness (palm oil), and both perform better than landfill gas to power projects. The particularly good performance of composting projects regarding the sustainable use of land resources, where they surpass all other project types thanks to the high value of compost as soil conditioner, contributes to their high scoring. A different situation is observed when comparing the projects regarding their sustainable use of fossil fuel. However, the poor score for composting within this criterion is not necessarily reflected in reality to the same extent because the capacity of compost to replace fossil energy intensive chemical fertilizers has not been taken into account in the assessment. Furthermore, our results imply that the sustainability rents of composting projects strongly depend on the project quality. Therefore we propose a list of sustainability requirements for composting projects, which has been compiled using literature research and expert interviews and contains manifold aspects related to project quality. Issues like compost quality, stakeholder inclusion, job generation potential, and labour rights are included due to their great importance for assuring high sustainability rents.

In conclusion, composting projects have a higher potentials for both GHG reduction and contribution to sustainable development than landfill gas projects. At the same time, they are financially dis-incentivised by the UNFCCC, a paradox which could be solved by two means: first, by modifying the methodology for the calculation of the emission reductions in order to generate high cash-flows earlier on, second, by remunerating projects for their sustainability contributions. The latter could be assured by sustainability labelling organisations making projects eligible for their sustainability labels or, in a more comprehensive manner, by taking into account the sustainability contributions in the crediting process of the UNFCCC under a post-Kyoto agreement.

Annex

Table A Origin and area of expertise of experts involved in the elaboration of sustainability requirements

Origin	Area of expertise
The Netherlands	Composting projects in developing countries
Indonesia	CDM project implementation
Switzerland	Compost quality
Cameroon	Composting in developing countries
Switzerland	CDM and measurement of sustainability
Switzerland	Water and Sanitation in developing countries

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Annex I

Paper 5

Climate policy's impact of on the rate and direction of corporate innovation activities – a survey of the European electricity sector

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- Under review for Environmental Innovation and Societal Transitions –

Abstract

The introduction of climate policy is one means of redirecting and accelerating technological change by altering the business environment of relevant actors, especially firms. This article aims at empirically assessing the impact of climate policy on technological change by focusing on the changes it causes in the rate and direction of corporate innovation activities. To this end, we develop a cross-sectional framework based on concepts from evolutionary economics and organisational theory on whose basis we derive hypotheses. We test these based on novel survey data on the electricity sector in seven EU countries. We find that while the EU ETS has limited and even controversial effects, long-term emission reduction targets are an important determinant of corporate innovation activities. Furthermore, technology policies are an important element of the policy mix complementing climate policy. Based on our findings recommendations for policy makers on how to improve the existing mix are derived.

Key Words: Technological Change, Innovation, Electricity Sector, Climate Policy, EU ETS, Technology Policy

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1. Introduction

Climate change requires rapid and significant technological change because a “business-as-usual” rate and direction is not sufficient to address the urgency of the problem (Pizer & Popp 2008). Hence, the debate about possible policies to initiate fundamental transitions towards low carbon pathways has been assigned a high priority on political and academic agendas worldwide (e.g., UNFCCC, 2011). “Technological change is at once the most important and least understood feature driving the future cost of climate change mitigation” (Pizer and Popp, 2008, p. 2768). The introduction of climate policy is one means of redirecting and accelerating technological change by altering the business environment of relevant actors, especially firms. This article aims to assess the impact of climate policy on technological change by focusing on the changes it causes in the rate and direction of corporate innovation activities. Based on this, recommendations for policy makers are deduced.

The effects of environmental policy on innovation have been examined by environmental economists (for literature surveys see e.g., Fischer and Preonas, 2010; Kemp and Pontoglio, 2008; Popp et al., 2010; Requate, 2005). Following a neo-classical tradition, most of these studies leave innovation as a “black box” with little consideration of the interactions of actors and their innovative activities (Jaffe et al., 2002; Taylor, 2008). Evolutionary approaches to technological change can help to open this black box and improve our understanding of what fosters technological transitions (Faber and Frenken, 2009; Rennings, 2000). However, there is a lack of a framework “which takes into account the interplay between relevant variables influencing environmental technological change and all the stages of this process” (del Río González, 2009, p. 861). First steps to develop such a framework have been taken (del Río González, 2009; Rogge et al., 2011b), but have not been tested quantitatively. The number of quantitative empirical papers specifically investigating climate policy and its innovation effects is rather limited (Zhang and Wei, 2010): studies are mainly based on purely theoretical models (e.g., Weber and Neuhoff, 2010) or on case-studies (e.g., Hoffmann, 2007; Rogge and Hoffmann, 2010; Rogge et al., 2011b). In order to test and extend the contributions of these papers, quantitative empirical analyses can deliver valuable insights.

Our study makes two contributions in this regard. First, we develop a framework mainly based on concepts from evolutionary economics complemented by organisational theory, namely a cognitive perspective, in order to consider a firm’s perception of its business environment (Anderson and Paine, 1975). In this framework, we make three important distinctions: we differentiate emissions trading and long-term emission reduction targets and consider further determinants external and internal to the firm (del Río González, 2009). In addition, and in order to holistically capture technological change we differentiate the rate and direction (by distinguishing emitting and non-emitting technologies) of research, development and demonstration (RD&D) as well as technology adoption. Lastly, as it is not only the regulated firms that are important for technological change, we consider relevant actors across the value chain, namely users and producers of technology (Lundvall, 1985; von Hippel, 1976). Based on this framework we derive hypotheses.

Second, we apply this framework to the European electricity sector in order to test our hypotheses. Currently the most GHG emission intensive sector, a massive decarbonisation of the electricity sector is needed in order to avoid dangerous climate change (IPCC, 2007, 2011). Besides end use efficiency measures, the International Energy Agency (IEA, 2010) identifies three main emission reduction levers: quick and large-scale adoption of renewable energies; substantial improvement of fossil electricity generation efficiency; and the development of carbon capture and storage (CCS) and its early adoption. A decarbonised electricity sector even has the potential for climate change mitigation in other energy related sectors, such as the transport sector via e-mobility (The Economist, 2010; van Essen and Kampman, 2011). As a consequence, one main target of the European Union Emissions Trading System (EU ETS) is the electricity sector (Ellerman et al., 2010). Furthermore, the EU emission reduction targets as in 2020 strongly affect the sector (Rogge et al., 2011b). In order to quantitatively test our hypotheses, we perform regression analyses on novel data from a survey of power generators and electricity generation technology providers in seven EU countries.

Our paper is structured as follows. We present our framework in section 2 and deduce hypotheses from it in section 3. In section 4, we provide an overview of the data and methodology used. While our results are presented in section 5, we discuss them and their policy implications in section 6. Finally, we summarize and conclude our study in section 7.

2. Theoretical framework

In our framework, we predominantly draw on evolutionary approaches which we complement with concepts from organizational theory, thereby applying theoretical pluralism, which allows us to “add value to existing approaches” (Costanza et al., 1997, p. 78). The strengths of evolutionary economics lie in its micro focus, i.e. the consideration of actors and their heterogeneity (Dosi, 1997; Faber and Frenken, 2009). As such, it provides insights into the motivations of firms to contribute to technological change and the role of external incentives (Dosi, 1988a). In order to include the firms’ internal ‘sense making’ (Weick, 1979), we draw from organisation literature and introduce a cognitive lens, which represents the interface between the firm’s environment and the firm level.

Accordingly, two levels are distinguished in our framework: the business environment external to the firm as perceived by the firm, and the firm itself with its innovation activities (see Figure 1). In the following sub-sections, we explain how we define the four main building blocks of our framework and their interactions: the dependent variable, i.e. changes in the rate and direction of innovation activities (2.1), is determined by climate policy (2.2), context factors (2.3), and the firm characteristics (2.4) Furthermore, we add a cognitive lens, through which a firm perceives its environment (2.5).

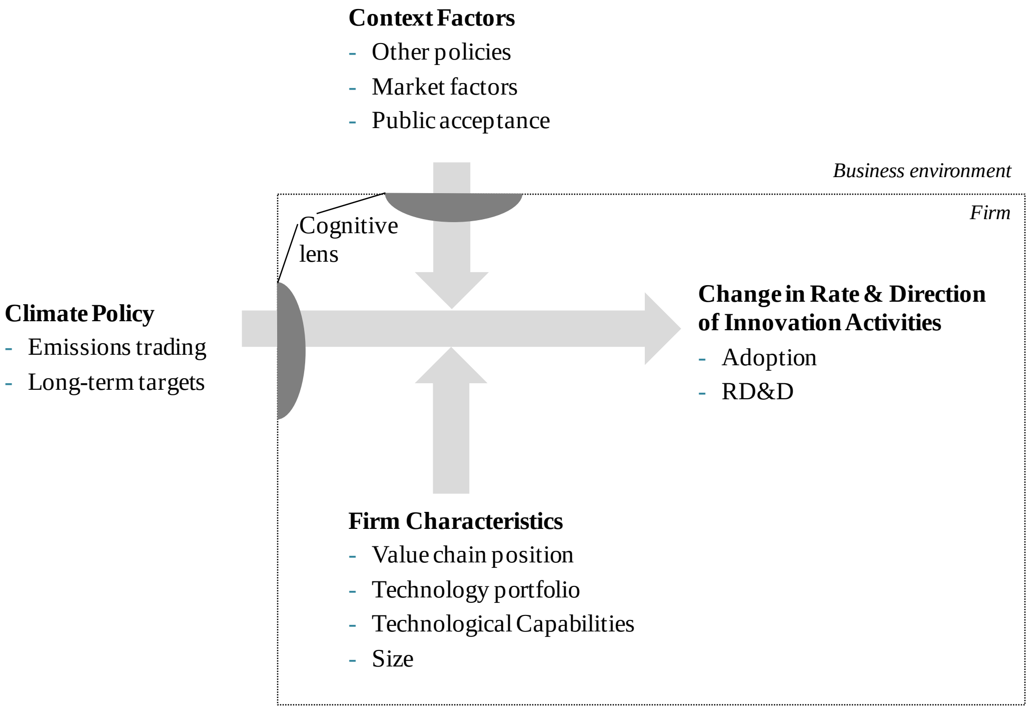

Figure 1: Theoretical framework

2.1. Changes in the rate and direction of innovation activities

Technological change is a non-linear process over time in which 3 stages, invention, innovation and diffusion of technology interact via feedback loops (Nelson and Winter, 1982; Schumpeter, 1942). Hence, models explaining such change should be of dynamic character. We follow this “methodological imperative” (Dosi, 1997, p. 1531) and explicitly consider the changes in innovation activity over time.

We distinguish two corporate innovative activities: Research, development and demonstration (RD&D) refers to activities from basic laboratory research activities, via the development of marketable products to the demonstration of pilot projects, and comprises invention and innovation; Adoption of state-of-the-art technologies refers to investments in new installations by users and represents the diffusion stage (Ashford, 1993; Jaffe et al., 2002). For each of these two innovation activities, we explicitly differentiate between the changes in the *rate* and *direction* of innovation activities (del Río González, 2009; Johnstone and Horbach, 2005). While the rate expresses the changes in overall adoption and RD&D activities, the direction reflects which technological alternatives these changes concern. For this, we differentiate between threatened, i.e. emitting, and aligned, i.e. non-emitting, technologies[1].

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[1] While fossil technologies (coal, gas, oil) are contributing to climate change and thus threatened by climate policy non-fossil technologies (renewables, nuclear) do not have any direct emissions and are thus aligned with climate policy.

2.2. Climate policy

We distinguish two elements of climate policy: first, emissions trading (ET) as a market-based policy instrument and second, long-term GHG emission reduction targets (LTT) which have been shown to be important for corporate innovation decisions (del Río González, 2008; Rogge et al., 2011b). ET and LTT are different elements of a policy mix (Kern and Howlett, 2009). The instrument ET represents a new cost or income factor for technology users, which depends on their over- or under-allocation with emission allowances and their effective emissions. From an evolutionary standpoint, it represents a demand-pull policy which directly influences the market's selection function. By changing the relative profitability of technologies it is likely "to stimulate the innovation and diffusion of technologies that facilitate compliance" (Jaffe et al., 2002, p. 46). Evolutionary theory suggests that LTT not only change current and future selection pressures amongst technological alternatives but also constitute market information which can serve as point of orientation for the relevant actors (McKelvey, 2005) and thereby "offer a stimulating long-term perspective" (Jänicke, 2011, p. 16). Such market information can influence the rate and direction of innovation activities (Dosi, 1982) as the permanence of LTT implies an obvious period of change in the business environment. If such change is "expected to endure beyond some critical threshold" firms will address it in their strategy (Dutton and Duncan, 1987, p. 283). Unlike ET, LTT, which are formulated on a national, supra-national (e.g., EU) and sector level (see e.g., European Commission, 2010; Herzog et al., 2006), need to be translated into firm level data by each firm in order to be incorporated in investment decisions.

2.3. Context factors

In addition to climate policy, several other factors in the business environment affect a firm's decisions regarding innovation activities (del Río González, 2009). Thus, we take into account three context factors in our framework. First, other important policies besides climate policy have been found to affect the innovation activities of firms (del Río, 2009; Fischer and Newell, 2008). These policies can either be based on technology-push or demand-pull mechanisms (Dosi, 1988b; Rennings, 2000). Second, market aspects, such as supply, demand and prices for important in- and output factors, influence a firm's innovation decisions (Newell et al., 1999). Third, the legitimacy of a technology, represented by its public acceptance, is an important determinant for technological change (Hekkert and Negro, 2009).

2.4. Firm characteristics

Firms are heterogeneous actors who react differently to external events (Dosi, 1997; Nelson, 1991; Schumpeter, 1942). To incorporate this heterogeneity, we include four firm characteristics in the framework. First we consider the value chain position of a firm, i.e., whether the firm is a user or a producer of technology, as a determinant for its innovative behaviour (Lundvall, 1985; von Hippel, 1976). Second, a firm's innovative activities will be affected by its technology portfolio because different technologies are differently affected by climate policy (Christensen and Rosenbloom, 1995) and – in the case of a technology user – existing installations might have to be replaced or extended. Third, technological capabilities are the basis of corporate learning (Penrose, 1959) and represent a firm's ability to address changing environments (Teece et al., 1997) because typically the higher a firm's technological capabilities the higher its tendency to react to external events with innovation (e.g. Horbach, 2008; Rosenberg, 1974). Fourth, addressing the neo-Schumpeterian scale hypothesis (see e.g., Scherer, 1965) we include the size of a firm. Also larger firms are usually equipped with more slack resources (Dimick and Murray, 1978), which allow them to react with higher investment rates during changes in their business environment (Cyert and March, 2005).

2.5. The role of perception

The inclusion of perceptions has a long tradition in organisational literature (dating back to March and Simon, 1958) and might be more adequate to explain corporate behaviour than basing models on purely objective data of the business environment (Anderson and Paine, 1975; Weick, 1979). Authors grounded in both organizational theory and evolutionary economics have recently expressed that the cognition plays an important role when explaining technological change and innovation (Kaplan and Tripsas, 2008; Nooteboom, 2009). In case of events or changes in the business environment, it is the perception of these shifts rather than the shifts themselves which shapes a firm's strategic choice (Barr, 1998; Dutton and Jackson, 1987; Kaplan and Tripsas, 2008; Ocasio, 1997).

Scholars separate perception into two elements: the attention which managers devote to a change in the business environment and the firm's interpretation of that change (Barr et al., 1992; Daft and Weick, 1984). The attention expresses to which extent a change in the business environment is an issue for the firm. Only changes that prompt a manager's high attention typically lead to changed corporate activities (Bansal, 2003; Barr et al., 1992). The interpretation reveals whether a firm-external change is seen as positive or negative for the firm (Barr et al., 1992; Sharma, 2000; Thomas et al., 1993). A different interpretation is likely to cause a different corporate reaction (Dutton and Jackson, 1987; Sharma, 2000). Furthermore, by looking into the future firms are able to anticipate external events and react prior to their occurrence (Ashford, 1993; Requate, 2005). This allows them to direct attention to and interpret future policy.

3. Hypotheses

We base our hypotheses on the assumption of stringent climate policy[2] and structure them along the dependent variables adoption and RD&D. For each of the two, we delineate the effects of

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[2] We will distinguish different levels of policy stringency from section 4 onwards.

emissions trading (ET) and long-term targets (LTT). We also distinguish investment changes in total (rate), in threatened and aligned new plants (direction).

3.1. The role of emissions trading for adoption

In order to react to changes in the business environment, users can adjust their technology portfolio via adoption of technologies with different characteristics on key performance dimensions (Anderson and Tushman, 1990) and thereby determine the diffusion of competing technologies (Nelson and Winter, 1982; Schumpeter, 1942).

Emissions trading (ET) regulates users of emitting technologies[3], who can choose to acquire emission allowances or invest in abatement technologies[4], whereby their behaviour is likely to depend on the perception of the policy (Sharma, 2000). Dutton and Jackson (1987, p. 84) argue that firms perceiving a change in their business environment as threat will take "actions of large magnitude", i.e. increase investments, in order to avoid losses and secure their survival. Conversely, firms with a positive perception of ET are expected to already be aligned with the aims of ET (or at least more than their competitors), which leads to "actions of smaller magnitude" (Dutton and Jackson, 1987, p. 84) that do not strongly alter the firm's adoption behaviour.

Hypothesis 1a : *The more negatively a firm perceives emissions trading the more it increases its total investments in new plants.*

Tradable permit systems, like ET, raise the propensity of the adoption of abatement technology (Frondel et al., 2007; Kerr and Newell, 2003; Popp et al., 2010). Though threatened state-of-the-art technologies also have the potential to reduce specific emissions, the sharpest emission reductions can be realized via the adoption of aligned technologies (McKinsey, 2007), lowering the need for allowances. In the case of a stringent design of the ET, high permit prices can raise the often lower generation costs of threatened technologies beyond those of aligned technologies (Hoffmann, 2007). For firms with a negative perception of ET, the adoption of aligned technologies is therefore more likely than the adoption of threatened technologies.

Hypotheses: *The more negatively a firm perceives emissions trading…*

1b) the more it decreases its investments in threatened new plants.

1c) the more it increases its investments in aligned new plants.

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[3] This refers to 'downstream emission trading' (such as the EU ETS), only. In 'upstream emission trading' the producers of fossil fuels are regulated (Woerdman, 2000).

[4] Under a stringent ET scheme, the investment in abatement technology is a more likely response than the acquisition of allowances (Jaffe et al., 2002; Sharma, 2000).

3.2. The role of long-term targets for adoption

LTT differ from emission trading as they represent a market information on a national or sector level and thereby rather serve as point of orientation (McKelvey, 2005) than representing a concrete cost factor such as emission allowances (Kirat and Ahamada, 2011). Their cognition allows firms to broadly evaluate their future business environment (Gavetti and Levinthal, 2000). To this end, LTT serve as indicator on the stringency of future regulation (Rogge et al., 2011b). Hence, firms in sectors with long-investments cycles might incorporate LTT into their investment decisions.

As for ET, we expect firms with a negative perception of LTT to increase their investments (Dutton and Jackson, 1987). Other than for ET, we also expect firms with a positive perception of LTT to also increase their total investments. This can serve to maintain and reinforce their competitive advantage over more emission intensive competitors in the long run, because stringent LTT might indicate a `green' paradigm shift (Freeman, 1992) which opens new window of opportunities (Geels and Schot, 2007; Tyre and Orlikowski, 1994). To sum up, the total adoption is increased by firms that perceive LTT as a threat as well as firms that perceive them as an opportunity. Hence, the reaction is independent from the interpretation. It rather depends on whether a firm directs its attention towards LTT or not, or put another way, whether firms perceive LTT as issue or not (Bansal and Roth, 2000; Barr et al., 1992).

Hypotheses 2a: The more a firm perceives long-term targets as an issue the more it increases its total investments in new plants.

Firms with a negative perception of LTT anticipate the need to adjust their portfolio to these targets and, thus, increase the investments of aligned technologies while reducing the investments in threatened technologies (Jaffe et al., 2002; Rogge et al., 2011b). Similarly, firms with a positive perception, in order to maintain their competitive advantage, strengthen their portfolio's share of aligned technologies over threatened technologies. Again the direction of innovation is independent of a firm's interpretation but depends on the attention directed to LTT (Bansal and Roth, 2000; Barr et al., 1992).

Hypotheses: *The more a firm perceives long-term targets as an issue …*
2b) the more it decreases its investments in threatened new plants.
2c) the more it increases its investments in aligned new plants.

3.3. The role of emissions trading for RD&D

RD&D activities aim to generate novelty (McKelvey, 2005) and thereby alter technologies on their future performance dimensions (Anderson and Tushman, 1990). However, unlike adoption decisions, RD&D investments are associated with extraordinarily high uncertainty regarding their outcomes (Scherer and Harhoff, 2000). In order to alter their technologies or technology portfolios, firms with a negative perception of ET will be more risk taking and willing to invest into uncertain RD&D, whereas firms with a positive perception will act more conservatively and do not increase investments into RD&D projects with an uncertain outcome (Wiseman and Gomez-Mejia, 1998).

Hypotheses 3a: The more negatively a firm perceives emission trading the more it increases its total investments in RD&D.

Firms with a negative perception can either increase RD&D investments in order to strongly reduce the specific emissions of threatened technologies (e.g. via efficiency enhancements or CCS) and/or in order to improve aligned technologies on other key performance dimensions (e.g., cost or reliability) (Rogge et al., 2011b). Firms with a positive perception of ET will likely not see a need to adjust the performance of the technologies in their portfolio. On the contrary, technology producers with a very positive perception might even shift away resources form RD&D towards new production capacities in order to profit from the now present market opportunities provided by ET (Cyert and March, 2005; Lavie et al., 2010).

Hypotheses: The more negatively a firm perceives emission trading…
3b) the more it increases its investments in RD&D of threatened technologies..
3b) the more it increases its investments in RD&D of aligned technologies.

3.4. The role of long-term targets for RD&D

In sectors with long R&D cycles, firms include information which concerns the longer-term future in their RD&D decisions (Chen, 2008; Inderrieden et al., 1990). Hence, LTT are an important point of reference indicating the stringency of future climate policy instruments (Rogge et al., 2011a) and thus expected to be very influential for RD&D decisions.

As for ET, firms with a negative perception of LTT are expected to increase total RD&D investments as a means of improving their technologies and thereby adapting their portfolios to the LTT. However, LTT also have a strategic relevance for firms with a positive perception. For them, LTT can be an indicator for increasing future markets due to paradigm shifts (compare Section 3.2). Therefore, they are likely to improve their technologies for the requirements of these markets via increased RD&D. As for LTT and adoption, the RD&D investment decision will not depend on a firm's interpretation but on the attention a firm directs to LTT (Bansal and Roth, 2000; Barr et al., 1992).

Hypotheses 4a: The more a firm perceives long-term targets as an issue the more it increases its total investments in RD&D.

Firms with a negative perception of LTT increase their RD&D activities in order to align their technologies and portfolios (see Section 3.3). We also expect firms with a positive perception of LTT to increase RD&D to make their technologies market ready – be it technologies that significantly reduce specific emissions or aligned technologies, which underperform on other performance dimensions. By doing so they prepare for jumping through the window of opportunity implied by LTT (see Section 3.2).

Hypotheses: *The more a firm perceives long-term targets as an issue…*

4b) the more it increases its investments in RD&D of threatened technologies.

4c) the more it increases its investments in RD&D of aligned technologies.

4. Data and methodology

In order to test our hypotheses we collected novel quantitative data in a survey of power generators (i.e. users) and electricity generation technology providers (i.e. producers). In the following, we describe the operationalisation of the survey variables (4.1), the roll out of the survey and the composition of the final sample (4.2) as well as the statistical methodologies we applied (4.3).

4.1. Variables

Changes in innovation activities

To measure the dependent variable, i.e. *changes in innovation activities,* we compare the innovation activities of the last five years (from the EU ETS' introduction in 2005 to 2009) with those of the previous five year period (2000-2004), before the ETS was effective. We query how the investment volumes in new plants and in RD&D have changed in the second five year period compared to the first one in a five-point Likert scale ranging from "dropped sharply" via "no change" to "rose sharply" (for the detailed questions see Appendix). For adoption we take into account all users, i.e. power generators, as all of them have to adopt technology at some point in time. For RD&D we take into account all power generators and technology providers that perform RD&D.

For the *rate of innovation,* we inquire the delta of total investments in RD&D and adoption, respectively. For the *direction of innovation,* we proceeded as follows. Firms were asked to score the investment change over time for all relevant technologies individually[5]. We then aggregate the answers per technology to a threatened and an aligned variable[6] via arithmetic averaging.

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[5] As our data is measured in relative terms per firm and not weighted with the turnover, our sample composition does not reflect the investment actions on a sectoral level.

[6] Under threatened technologies, we subsume lignite, hard coal and gas based electricity generation technologies as well as CCS and combined heat and power (CHP) specific products. CCS per se is not threatened. It is not an

Perception of climate policy

While in our study long-term targets (LTT) represent European and global GHG emission reduction targets for 2020, emissions trading is represented by the EU ETS. Several authors have pointed to a lack of stringency in the first (2005-07) and second (2008-12) trading phases[7] of this mechanism, resulting in relatively low certificate prices (e.g., Betz et al., 2006; Ellerman and Buchner, 2007; Neuhoff et al., 2006). The third (2013-2020) phase of the EU ETS however is significantly more stringent, both in terms of the overall limit on emissions (cap) and the foreseen full auctioning for power generators from 2013 onwards (EU, 2008). Hence, we distinguish two periods of the EU ETS, i.e. ETS 1&2 (from 2005-12) and ETS 3 (from 2013-20)[8].

We queried the *perception of the climate policy* elements using a five-point Likert scale ranging from "very negatively affected" via "not affected" to "very positively affected", following the literature on cognition (Barr et al., 1992; Dutton and Jackson, 1987). In the case of LTT, we used the absolutes of these values to express the firm's attention, transforming the 5-point Likert scale used in the survey into a three-point scale from "not affected" to "very much affected".

Perception of context factors

The *perception of context factors* was operationalised in the same way as the one of ET, i.e. via a five-point Likert scale from "very negatively affected" via "not affected" to "very positively affected". For the selection of variables we took into account those context factors shown to be relevant in previous studies (e.g., Rogge et al., 2011b): For *other policies* than direct climate policy, we differentiate the perception of technology-push, i.e. R&D support[9], and RET specific demand-pull

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electricity generation technology but an end-of pipe solution intended to increase the alignment of fossil fuel based electricity generation technologies and hence the prolongation of the fossil, i.e. threatened, trajectories. While CHP can also be used with biogenic fuels, most of its RD&D and adoption takes place under the fossil fuel based regime. Nuclear and renewable electricity generation technologies (i.e. technologies based on wind, solid biomass, solar thermal, photovoltaic, biogas, geothermal and ocean energy) fall under the aligned category.

[7] In these phases, emission allowances were almost fully allocated based on the principle of grandfathering and free allocation for new plants (EU, 2003).

[8] Taking the period of 2005 to 2009 as a basis captures all relevant investment decisions. On the one hand, the over- or under-allocations were evident for each firm at the earliest by April of 2006 when the verified emission data was released (Rogge et al., 2006). In combination with long planning and permission activities we can expect a delay of investment decisions until the end of 2008. At that time, LTT and the design of ETS 3 had already evolved (European Parliament, 2008). On the other hand, firms planning to profit from free allocations have to commission their plants before 2013 and hence had to take their investment decisions no later than end of 2009 due to the long construction time of fossil plants (Roques et al., 2008).

[9] The perception of national as well as EU R&D support policies are queried separately and subsequently combined via a factor analysis.

policies such as feed-in-tariffs. Regarding *market factors* we include the perception of prices and supply of fuels, as they strongly determine the cost of electricity generation and hence the relative competitiveness of all technologies. Furthermore, we consider prices and the demand for electricity because they are the strongest drivers on the revenue side of firms in the sector. The perception of *public acceptance* refers to coal-based technologies, as they represent the largest contributor to the sector's GHG emissions and have been subject to controversial public debates (Reuters, 2008).

Firm characteristics

In total, we consider four *firm characteristics*. For the *value chain position,* we introduced a dummy variable which differentiates technology users, i.e. power generators, from producers, i.e. technology providers. A firm's *technology portfolio* is described via two variables: first, the share of threatened technologies in the portfolio[10] and, second, for adoption, the need to replace or extend existing generation capacity. While the former variable is described in percentage points, the latter was polled on a five-point Likert scale from "no need" to "strong need". *Technological capabilities* "comprise the physical and knowledge capital stock of a firm to develop new products and processes", referring to both financial and human capital (Horbach, 2008, p. 164). To represent technological capabilities, we factorised two commonly used items – percentage of R&D expenses per turnover (Cohen and Levinthal, 1990) and percentage of R&D employees per overall staff (Horbach, 2008) – into one indicator (Kaiser, 1960)[11]. The *size* of the firm is quantified via its turnover, which was measured in 6 exponentially rising categories. The entire set of variables, the question and answer categories as well as their descriptive values can be found in Table A2 in the Appendix.

4.2. Procedure and Sample

The survey was conducted on our own account in seven EU countries (see Table A1 in the Appendix) end of 2009, i.e. before the end of the UNFCCC Conference of the Parties in Copenhagen (COP 15). Subsequent to a series of pre-tests, the survey was translated into each respective language and a reverse translation was independently conducted in order to guarantee equality in meaning. After contacting each firm by telephone, invitations for the online survey were sent to a senior manager of each firm. The results presented in this paper are based on the answers of 65 power generators and 136

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[10] For power generators this is the generation portfolio, for technology providers this is the sales portfolio.

[11] As for all supplier dominated sectors, in the power sector the rate of R&D activity strongly differs between users and producers of technology (Pavitt, 1984). Hence, we standardized the variable per value chain step before merging the samples.

technology providers[12]. This translates into response rates of 14.6% and 13.1% out of the 495 power generators and 1086 technology providers identified among the population[13].

In our sample, 80% of the power generators have undertaken adoption measures, i.e., invested in new plants during the last ten years. Of the power generators, 38% have invested in RD&D within the last ten years. As expected, the number of technology providers with RD&D activities is much higher, namely 77%[14]. These numbers result in a total of 65% of the respondents (130 firms) being included in the regressions on RD&D. More details on the sample can be found in Figures A1 and A2 in the Annex.

4.3. Statistical Methodology

In order to test our hypotheses, we applied multivariate linear regression analyses based on ordinary least squares and with forced entry of predictors. We conducted six regression analyses, as we are looking at adoption and RD&D each on the level of total, threatened and aligned investments, leading to six dependent variables.[15]

In order to arrive at consistent models without omitting variables and at the same time allow for good results despite the relatively low number of observations, we tested our model with several combinations of variables, including a number of variables which are no longer present in the final model[16] presented in section 5. None of the excluded variables showed significance at a $p<0.1$ level in any model and did not notably increase the explanatory power (R sq.) of the models.

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[12] In the TP sample, a large part of the firms is active in RET, only. This is due to characteristics of the population with its relatively few large threatened technology providers and its many small and medium sized renewable technology providers.

[13] The population of power generators in each country was identified based on the EU's Community Independent Transaction Log (CITL) which comprises all firms that fall under the EU ETS. The population of technology providers in each country was identified on the basis of the KKS power plant classification system, the European firm registry Amadeus and the respective European industrial activity classifications (NACE Rev.2).

[14] The remaining 23% are technology assemblers without any R&D budgets. As we only take into account firms that actually pursue RD&D in the RD&D models, these assemblers are not part of our regression models.

[15] Missing values within the independent variables were replaced with the value chain step’s sample mean of the respective variable (De Vaus, 2001). In the adoption model, 2 % missing values were replaced (control variables only), with none of the variables exceeding 6.2 % replacements. In the RD&D model, 2.6 % missing values were replaced, also with none of the variables exceeding of 6 %.

[16] Additional variables we tested and which are not present in the final models were: *Perception of public acceptance for nuclear energy; Perception of public acceptance for CCS; Perception of equipment prices; Perception of general electricity market regulation; CO2 intensity of production portfolio; Environmental capabilities; Share of home market in total sales;*

Additionally we performed several tests. We checked for multicollinearity via a correlation matrix (see Table A2 in the Appendix) and the variance inflation factor (VIF) (Myers, 1990). None of the correlation coefficients and VIFs exceeds the respective tolerance values.[17] To control for common method bias we performed Harman's one-factor tests, whose results[18] suggest that common method bias is not present in our dataset. Finally, we checked our model choice via three measures: a test for heteroscedasticity (Allison, 1999), a test for normality of the residuals (Q-Q-plots) and the Durbin-Watson statistics (Field, 2009). All tests showed good results[19] and corroborate the choice of our model.

5. Results

The descriptive results (see Table A2 in the Annex) highlight that on average power generators have moderately increased the adoption in total and the adoption of threatened technologies in the last 5 years. Aligned[20] investments in new plants experienced a stronger rise. Regarding RD&D, total and aligned experienced a higher increase than threatened RD&D activities which were moderately augmented. The results section is split into two sub-sections, one on adoption and one on RD&D, which each address the effects of the climate policy elements along the hypotheses. For ET we distinguish ETS 1&2 and ETS 3. Above that, we describe and explain all significant effects of further variables.

5.1. The role of current climate policy for adoption

Our regression analysis (see Table 1) indicates a positive relationship ($p<1\%$) of ETS 1&2 and the total rate of adoption by power generators (*Model 1*). Accordingly, firms with a more positive perception increase their total investments which contradicts *Hypothesis 1a.* When looking at the directions our analysis suggests that ETS 1&2 has a significant ($p<5\%$) positive effect on threatened (*Model 2*) adoption. Hence, for ETS 1&2, *Hypothesis 1b* is seemingly supported. However, while the

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[17] The maximal absolute correlation coefficient between independent variables is 0.632 and hence below the threshold of 0.8 (Schendera, 2008). All VIFs in our models are well below the critical maximum threshold of 10 (Myers, 1990).

[18] The Harman's one-factor tests for adoption and RD&D resulted in four factors each, whereby the first factor only accounts for 23% (adoption) and 32% (RD&D). This means more than one factor emerges with the first factor explaining less than half of the variance, suggesting common method bias is very unlikely (Podsakoff et al., 2003).

[19] All heteroscedasticity tests showed no patterns between the variance and the predicted values, all Q-Q-plots resulted in lines revealing a normal distribution of residuals, and all Durbin Watson factors were close to 2 (between 1.436 and 2.264). justifying the assumption of independent errors.

[20] As none of the firms in the sample has invested in new nuclear generation capacity in the last ten years, the adoption of aligned technology refers to RET only.

hypothesis assumed that more negatively affected firms reduce investments more, we suspect the reverse effect: the more positively firms perceive ETS 1&2, the more they increase threatened investments. This might seem surprising but can be explained by the low stringency of ETS 1&2, both in terms of the generous cap and resulting low CO_2 prices and in terms of the free allocation. Power generators with threatened plants reaped windfall profits (Sijm et al., 2006), and firms investing in new threatened plants benefitted from a large subsidy effect (Ellerman and Buchner, 2007), leading to a positive perception by many firms. The resulting increased investments in new threatened plants also impinge on total investments due to the typically large size of such investments (compared to investment in renewables). At the same time, we do not observe any significant relationship between ETS 1&2 and the adoption of aligned technologies (*Model 3*) in our data, implying that *Hypothesis 1c* is not supported. The corresponding CO_2 prices caused by the ETS 1&2 seem to be too low to affect the competitiveness of aligned relative to threatened plants and thereby significantly support investments in new aligned plants.

The more stringent ETS 3 and the total rate of adoption are negatively related ($p<5\%$) implying support for *Hypothesis 1a*. A more negative perception of this policy element apparently triggered increased total investments. However this relationship is not observed for a distinct direction as we neither find any significant relation for threatened (*Model 2*) nor for aligned technologies (*Model 3*). This leaves *Hypotheses 1b* and *1c* unsupported. Correspondingly, we assume that firms which increase investments due to ETS 3 follow heterogeneous strategies with some choosing to invest in the threatened, others in the aligned and yet others in both directions.

Other than expected in *Hypothesis 2 a-c*, we do not observe any significant relation of LTT and the adoption decisions of power generators (*Model 1 to 3*). Firms' investments in new installations are very much determined by the expected payback of these investments and the associated risk, which are both affected by ET directly and measurably (Hoffmann, 2007). Contrary to that, LTT are not specified for individual companies and therefore hard to factor-in for their decision making.

Table 1: Results of the regression analyses (standardized coefficients)[21]

	adoption			RD&D		
	in total	threatened	aligned	in total	threatened	aligned
	Model 1	*Model 2*	*Model 3*	*Model 4*	*Model 5*	*Model 6*
perception of climate policy						
ETS 1&2 (2005-12)	0.320 **	0.319 *	0.018	.053	.007	.206
ETS 3 (2013-20)	-.313 *	-.289	-.211	-.069	-.199	-.284 *
LTT (as issue) (2020)	.056	.006	.187	.238 **	.068	.231 **
perception of context factors						
technology push policies				.097	.399 *	.220 *
RET demand-pull policies	.237 *	.013	.363 **	.133	-.106	-.075
fuel prices	-.073	.121	-.185	-.147	-.180	-.179
electricity prices	.124	-.012	-.003	.201 *	-.018	.294 **
public acceptance for coal	.186	.230	.089	.177 *	.113	.202 *
firm characteristics						
value chain position				.176	.264	.085
share fossil	-.024	-.020	-.294 *	.118	.396 *	-.181
need to replace/extend capacity	.346 **	.113	.168			
technological capabilities				.116	.392 *	.311 **
size	.403 **	.438 **	.010	.195 *	.428 *	.220 **
model fit						
R sq.	0.567	0.353	0.321	.285	.524	.445
adjusted R sq.	0.487	0.233	0.196	.212	.313	.374
N	65	65	65	130	40	107

** Significant at the p<1% level. * Significant at the p<5% level

Of the context factors, only RET promotional policies significantly relate to adoption. Firms with a positive perception of these policies increase their aligned investments (*Model 3*, p<1%) to an extent which affects total investments (*Model 1*, p<5%). Regarding firm characteristics our data suggests that firms with a higher share of aligned technologies in their portfolio tend to increase their adoption of aligned technologies (*Model 3*, p<5%), which implies a certain path dependency of firms with respect to their technology portfolios. The replacement need is a strong determinant of total investments (*Model 1*, p<1%) but has no significant relation with the technological direction (*Model 2 and 3*). Finally, we find that the size of the firm has a positive relationship with the adoption tendency in total (*Model 1*) and that of threatened (*Model 2*) technologies (both at p<1%). Due to their resources, larger firms might be able to react by investing more and into larger units, such as threatened plants.

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[21] The regression table including the non-standardised coefficients and their standard errors is available upon request.

5.2. The role of current climate policy for RD&D

Neither ETS 1&2 nor ETS 3 show a significant relationship with firms' total (*Model 4*) and threatened (*Model 5*) RD&D decisions. *Hypotheses 3a* and *b* are hence not supported. Also for aligned technologies (*Model 6*), ETS 1&2 does not significantly relate to RD&D decisions. The only ET relation we do observe is that of ETS 3 (p<5%), which suggests support for *Hypothesis 3c*. Firms with a negative perception of ETS 3 increase their RD&D in aligned technologies while those with a positive perception reduce it. The fact that only RD&D of aligned technologies is affected could be based on the development times of RET, which are usually shorter than those of threatened technologies (IEA, 2008).

We observe significant (p<1%) relations of the perception of LTT and total (*Model 4*) and of aligned RD&D activities[22] (*Model 6*), supporting *Hypothesis 4a* and *4c*. In contrast, regarding RD&D of threatened technologies (*Model 5*) we do not find support for *Hypothesis 4b*. While other studies suggest effects of emission targets especially on RD&D of CCS (Hoffmann, 2007; Rogge et al., 2011b), only very few, large firms (in the entire population as well as in our sample) pursue RD&D of this technology, reducing their statistical impact on the entire sample.

We detect several significant context factors in the RD&D models. A positive perception of technology-push policies seemingly drives investments in threatened (*Model 5*) as well as in aligned (*Model 6*) RD&D (both at p<5%). Positive effects of R&D support programs (e.g., EREC, 2010; European Commission, 2008, 2009) are predicted by theorists (e.g., Dosi, 1988a). Interestingly, RET specific demand-pull instruments do not seem to directly trigger RD&D in the aligned direction. In this regard, a recent study shows that very generous RET demand-pull policies draw the focus from explorative research to rather exploitative development and production (Peters et al., 2011). According to our data, the more positively a firm perceives the development of electricity prices, the main determinant for all firms' past, present and expected future revenues in the sector[23], the more it seems to increases total (*Model 4*, p<5%) as well as aligned (*Model 6*, p<1%) RD&D investments.

Firms with a positive perception of the public acceptance of coal appear to increase aligned (*Model 6*) RD&D, which impinges upon total (*Model 4*) RD&D (both at p<5%). As the public acceptance for coal in Europe has decreased over recent years (Eurobarometer, 2006), firms with non-coal based technology portfolios perceive the acceptance positively and may interpret it as a future demand driver. Thus, they improve their technologies via increased R&D.

Regarding firm characteristics, our analyses propose that the higher the share of threatened

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[22] Our results on threatened RD&D activities and the interpretation thereof must be read with caution due to the low number of observations (40) compared to the number of independent variables (12).

[23] As such, electricity prices strongly influence a firms' availability of financial resources to be invested in RD&D. Hence, we assume that rising electricity prices are perceived positively. As power generators' streams of income are directly coupled to the electricity prices, this argumentation also refers to technology providers.

technologies in a firm’s portfolio the more it tends to increase RD&D of threatened technologies (*Model 5,* p<5%). This highlights the role of firm-internal path dependencies in aligning their technologies to the aims of climate policy and thus defending their business. In line with other scholars (e.g., Horbach, 2008; Rosenberg, 1974), we suggest that higher technological capabilities trigger more RD&D in both threatened (*Model 5,* p<5%) and aligned (*Model 6,* p<1%) technologies. The positive relationships we find regarding the firm size (*Model 4 to 6*, at p<5% for total and threatened and p<1% for aligned investments) can be explained by resource slack, which raises a firm’s willingness to take risks and invest in RD&D (e.g. Greve, 2003).

Table 2 summarizes all results with regard to our hypotheses. It becomes apparent that the relatively lax ETS 1&2 and the more stringent ETS 3 have several opposing effects.

Table 2: Overview of hypotheses and the results

No.	**Expected effect**		**Results**	
1a	The more negatively a firm perceives emissions trading the more it…	increases adoption in total.	ETS 1&2: ETS 3:	contradicted supported
1b		decreases adoption of threatened technologies.	ETS 1&2: ETS 3:	seemingly supported, but reverse effect not supported
1c		increases adoption of aligned technologies.	ETS 1&2: ETS 3:	not supported not supported
2	No effect of long-term targets on adoption decisions.			supported
3	No effect of emissions trading on RD&D decisions.		ETS 1&2: ETS 3:	supported supported, except for non-fossil RD&D
4a	The more a firm perceives long-term targets as an issue the more it…	increases RD&D in total.		supported
4b		increases RD&D of threatened technologies.		not supported
4c		increases RD&D of aligned technologies.		supported

6. Policy implications

Decarbonising the electricity sector, which is the main aim of climate policy, translates into an immediate increase of adoption of aligned technologies and of RD&D for both threatened and aligned technologies (IEA, 2010). Despite the high relevance of the topic, so far little empirical evidence on the effects of the current policy mix has been presented (Ellerman et al., 2010). Our analyses suggest several effects of climate policy and other elements of the policy mix. The aim of this section is to discuss three major results. For each result, we show its implications on technological change in the sector, second, relate it to the current academic debate and, third, derive policy recommendations on how to improve the current policy mix.

6.1. Adverse effects of lax design should be avoided

Our results show that the EU ETS in its early phases (1&2) neither triggered investments in the adoption of aligned technologies nor in RD&D. The only effect we do observe, namely the increased adoption of threatened technologies, undermines the goal of substantial GHG emission reductions. The short period of allocating free allowances to new threatened plants and forfeiting allowances of closed threatened plants is causing long-term future GHG emissions. Thereby ETS 1&2 increased the lock-in into fossil centralised power generation, as particularly large firms seem to have increased the adoption of these technologies, which are characterized by relatively long lifetimes and large sunk costs[24]. Furthermore, our results show that firms focusing on threatened technologies hesitate to invest in aligned technologies, illustrating a self-reinforcing lock-in effect. This makes a lax ET design even more detrimental.

While the current academic debate has recognised that a lax ET design might result in effects opposing to the intended effects (del Río González, 2008; Ellerman et al., 2010; Sijm, 2005), and “theoretical arguments are abundant and clear [...], empirical evidence on the predicted effects [of the EU ETS early phase and its design] is scant” (Ellerman et al., 2010, p. 289). At this point our study makes an empirical contribution.

The laxity of the first phases of the ETS was intended to increase political acceptability and was planned to be tightened from the beginning (Ellerman et al., 2010). Policy makers in regions which also plan to introduce ET, e.g., China (United Nations, 2011), should be aware of the potential counterproductive consequences of a too lax ET design. In Europe, while it is too late to adjust the initial EU ETS design now, the EU should guarantee a minimum stringency for phase three. While the fact that Germany recently decided to phase-out nuclear power plants until 2022 is expected to cause rising allowance prices (Point Carbon, 2011), tightening the emission caps would further increase the

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[24] Due to the sunk costs and lock-in effects, RET need to become even more cost-efficient in order to compete with the marginal electricity generation costs of these threatened plants.

stringency of the ETS. The auctioning of emission rights, as provided for in the power sector from 2013 onwards (ETS 3), is one way of better incentivising investments in aligned technologies (Hepburn et al., 2006). The free allocation methods of those member states which are subject to exemptions from full auctioning should be strictly supervised by the EU in order to avoid similar effects as observed under ETS 1&2. Furthermore additional allocations should incentivise firms which are pro-active in strong GHG emission reducing measures via adoption and/or RD&D. The European Commission's thoughts on an "innovation/ technology accelerator" (European Comission, 2010, p. 75) for industrial sectors go in this direction and might be applied also to the power sector. Outside of the power sector, firms in industrial sectors partly remain subject to free allocations via benchmarks under the ETS 3. These benchmarks should be designed in a stringent manner.

6.2. Technology-push policies and LTT important to complement minor effects of ET on RD&D

Our results show the importance of technology-push measures for RD&D. While ET only affects RD&D of aligned technologies, R&D support policies led to increased RD&D of both aligned and threatened technologies, which is important for moving all levers identified by the IEA (see Section 1). Our results furthermore highlight the role of LTT as driver for RD&D. They have an orienting function and might, if stringent and credible, indicate a long-term paradigm shift. The long-term nature and high uncertainty of RD&D let LTT appear more important than the effective instrument ET, according to our data. However, LTT and ET interact. First, the credibility of LTT depends on the stringency of instruments that support these targets (Rogge et al., 2011a; Rogge et al., 2011b). Second, LTTs' role might be especially important if climate policy is realized via market based instruments such as ET: compared to command-and-control policies, they allow a much greater freedom of choice for concerned actors (Frey, 1997; Smith and Sorrell, 2001). This freedom makes finding an optimal response strategy more difficult for a firm, resulting in a higher need for orientation, provided by LTT.

In the academic debate, authors mainly from the neoclassical strand promote one single "technology neutral" market based policy (Azar and Sandén, 2011, p. 135) which addresses the negative externality GHG emissions and typically prefer ET over other instruments (e.g., Böhringer and Rosendahl, 2009). Contrarily, innovation scholars stress the role of spillover effects and high uncertainty of RD&D investments for private sector RD&D leading to private underinvestment in RD&D (Griliches, 1992; Jaffé et al., 2004; Sagar and van der Zwaan, 2006; Scherer and Harhoff, 2000). Technology-push policies in the form of R&D subsidies are suggested as complementary policy option to address these externalities (Goulder and Parry, 2008; Sagar and van der Zwaan, 2006). Our results support this view as the relatively stringent ETS 3 only has an (not entirely supportive) effect on RD&D of aligned technologies. The role of LTT, whose importance we show in our study, is so far underrepresented in the academic debate.

For policy makers this implies that RD&D support and LTT should be part of an integrated mix which complements ET. While ETS 3 seems to be “congruent” (Kern and Howlett, 2009, p. 395) with LTT to a large extent, it is certainly not the case for ETS 1&2 due to its lack of stringency[25]. In order to provide good orientation and increase the predictability of climate policy, an important aspect for corporate investment decisions (Engau and Hoffmann, 2011; Hoffmann et al., 2009), LTT should be solid and clearly communicated. Besides the European emission reduction targets[26], the approval of an ambitious post-Kyoto agreement could provide such orienting function. Furthermore, LTT need to be congruent with the existing policy instruments. While this seems to be the case for the European long-term targets and ETS 3 to some extent, it is certainly not the case for LTT and ETS 1&2 In order to avoid such incongruence, “ambitious and realistic” LTT “at the limits of the capacity that is technically feasible for a country” (Jänicke, 2011, p. 18) should be formulated first. Based on these targets, it is crucial that congruent instruments are installed in order to make the LTT credible (Rogge et al., 2011a). A breach of this order raises the risk of incongruent targets and instruments (Kern and Howlett, 2009). As transformations of infrastructure sectors are long-lasting processes which experience a lot of resistance from established threatened regimes (Grübler, 1990; Grübler et al., 1999) the political practice with its short-term focus and electoral cycles struggle with mapping the pathways for transitions (Meadowcroft, 2011) and providing reliable LTT. This stresses the role of supra-national institutions, such as the EU or the UN, which are able to think and act in longer cycles and more independently from politics of parties than national governments (Gabel, 1998; Schmidt, 2006), for setting and defending targets.

The distribution of RD&D funds among different technologies is fundamental in order to not pick the “wrong winners” (Azar and Sandén, 2011; Hall, 2002) and should be based on clearly set “research priorities” (Azar and Sandén, 2011, p. 136). Such priorities should clearly reflect the LTT that the government aims to achieve with the policy mix.

6.3. To harvest production-based cost reductions, technology-specific demand-pull policies are essential

Our study reveals that neither ETS 1&2 nor ETS 3 was capable of triggering increased aligned technology adoption. Only RET- pull policies had this effect. According to our analysis, RET-pull policies are in fact *the only* firm-external factor triggering the adoption of aligned technologies according to our analyses. Therefore, these policies are essential to avoid a lock-in into currently cheaper technologies positively affected by ET which, however, might come at higher cost and/or lower emission reductions in the long-run (del Río González, 2008).

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[25] Compare the switch of the sign between ETS 1&2 and ETS 3 for total adoption in Model 1.

[26] Instead of the long lasting debate on whether to increase the targets from 20 to 30% by 2020 (The Guardian, 2010), an early and unequivocal decision for the more ambitious target would have been a clear signal to the relevant firms.

Scholars have shown that (aligned) technologies further away from competitiveness typically have the steepest learning curves (Junginger, 2010; Sorrell and Sijm, 2003). However, permit prices of an ETS are often not enough to close the present profitability gap between these and the dominant technologies (Rogge et al., 2011b). Pure "technology-neutral" market based policies such as ET thus pick the wrong winners (Azar and Sandén, 2011). Therefore, to avoid a lock-out of new aligned technologies and allow for increasing spill-over effects within the attached technology clusters (Bergek et al., 2008; Lim et al., 2003), additional technology-specific demand-pull policies are called for (Azar and Sandén, 2011; Jacobsson and Bergek, 2004). They foster production based cost reductions via learning by doing, bring the technologies closer to competitiveness, potentially decrease long-run abatement costs (Azar and Sandén, 2011; del Río González, 2008; Sorrell and Sijm, 2003) and can also increase the credibility of LTT (Rogge et al., 2011a).

For policy makers this means that technology-specific demand pull policies ought to be another integral part of a policy mix aiming at the decarbonisation of the electricity sector. In order to minimize costs and provide incentives for RD&D, cost monitoring and corresponding reductions of the support are essential, especially as the steep learning curves result in fast cost reductions (Peters et al., 2011). This means, while LTT should be fixed, policy making needs to by dynamic by adjusting instruments to the alternating competitiveness of technologies and thereby meet the dynamic character of technological change (Sartorius and Zundel, 2005).

Furthermore, the integration of new technologies into an "open assembled system", such as the electricity sector, might necessitate the development and diffusion of "interface and linkage technologies" (Tushman and Rosenkopf, 1992, p. 331). For instance, in the case of an ample diffusion of intermittent RET, more and potentially new storage technologies or different grid management (see e.g. the current smart grid approaches) might be necessary and imply learning on a system level (Sagar and van der Zwaan, 2006). Hence, demand-pull policies for new technologies should be coupled with policies addressing the enabling environment of these technologies.

7. Conclusion

Our study contributes both on a theoretical and an empirical level to the extant literature on how to politically induce environmental technological change. We combine evolutionary economic elements and cognitive organizational theory in one “integrated conceptual framework” (del Río González, 2009, p. 861) for analyzing the role of climate policy for technological change. Taking into account other determinants, we empirically analyse the effects of climate policy on the rate and direction (by distinguishing threatened and aligned technologies) of RD&D and adoption of relevant firms in the electricity sector. We find that the mis-design of the first two phases of the ETS has created incentives leading to the increased adoption of threatened technologies. Moreover, the more stringent ETS 3 has only limited effects on the rate and direction of corporate RD&D and adoption. Conversely, long-term emission reduction targets are an important trigger of RD&D. Finally, technology policies in the form of additional demand-pull and technology-push instruments have significant effects on low-carbon technological change and are instrumental in compensating for the insufficient effects of ET. Our study thereby empirically supports the need for a more stringent ETS as part of a policy mix in order to steer the rate and direction of technological change, a non-linear process characterized by lock-ins, towards low-carbon. Based on these findings we offer several points for improvement of the existing mix. The theoretical contribution of our paper lies in including organisational cognitive theory in the study of determinants of (green) technological change. The historic study of energy services by Fouquet (2008, p. 355) shows that one “source of change is beliefs and knowledge”. While evolutionary studies implicitly contain cognitive elements partly explaining the bounded rationality of firms (see e.g., Dosi, 1982; Dosi et al., 1997), making explicit the role of actors’ perceptions allows to include the actors’ sense making of their selective environment and thereby to derive testable hypotheses. Only recently scholars have started to include cognitive organisational theories which try to explain firms’ strategy making into evolutionary innovation studies (Geels, 2010; Kaplan and Tripsas, 2008; Nooteboom, 2009).

Our analyses shows potential fields of future research for (sustainable) transition scholars. The role of policy perception, i.e., how much attention firms direct towards policies and how they interpret them depending on their characteristics is underexplored. While our paper represents a starting point, a study comparing the effects of objective and perceived policy stringency could yield deeper insights and feedback on how to formulate policy in order to prompt a high attention and the requisite interpretation. Furthermore, policy makers should be supported by transition scholars in finding the right policy mix. Hence, studies on the interaction effects of policy instruments and targets should be conducted. Especially the so far under-researched role and interaction of LTT with other instruments should be analysed in more detail in theoretical as well as empirical studies. Yet, in order to increase the influence of the evolutionary school, also the political practicability of evolutionary studies has to be a key feature. To this end, increasing the understanding of political processes in transition studies is an important avenue for future research (Meadowcroft, 2011).

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Appendix

Table A1: Country of origin of respondents

Group	France	Germany	Italy	Poland	Slovakia	Spain	UK
PG (65)	2%	49%	14%	15%	5%	15%	-
TP (136)	5%	38%	19%	8%	4%	21%	5%

The strong bias towards Germany is to great parts based on the very high number of (small) utilities in that country compared to the other countries. A similar trend can be observed in the technology provider sample. While France and the UK are clearly underrepresented in our sample, the other numbers roughly represent the entire population of electricity generation technology providers in the population.)

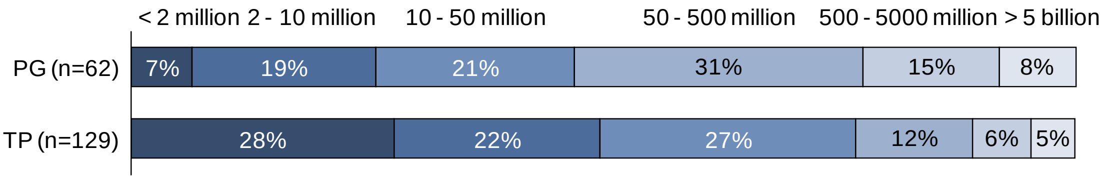

Figure A1: Size of the firms (the missing ten firms did not respond to this question)

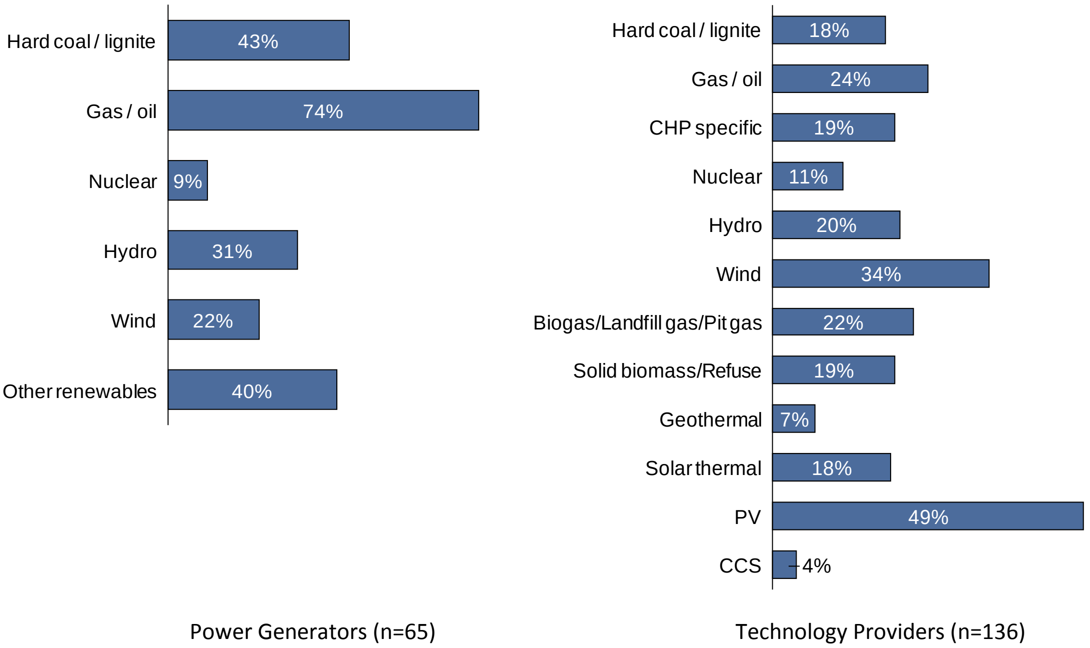

Figure A2: The firms' technology portfolios as in 2008 (The numbers show how many firms of the entire sample are active in the respective technology. Due to firms with mixed portfolios, the numbers do not add up to 100%)

Table A2: Descriptive statistics of variables used and questions as asked in survey

	variable name	"question asked" / *variable constructed*	potential range	power generators		tech providers		total sample	
				mean	std.dev.	mean	std.dev.	mean	std.dev.
dependent variables	total adoption	"How has your total investment volume for new installations changed in the last five years (2005-2009) compared to the previous five year period (2000-2004)?"	{-2,...,2}	0.54	1.24	-	-	-	-
	fossil adoption	"How has your fossil investment volume for new installations changed in the last five years (2005-2009) compared to the previous five year period (2000-2004)?"	{-2,...,2}	0.34	1.19	-	-	-	-
	non-fossil adoption	"How has your non-fossil investment volume for new installations changed in the last five years (2005-2009) compared to the previous five year period (2000-2004)?"	{-2,...,2}	0.44	0.93	-	-	-	-
	total RD&D	"How has your total RD&D investment volume changed in the last five years (2005-2009) compared to the previous five year period (2000-2004)?"	{-2,...,2}	0.68	1.07	0.91	0.93	0.87	0.96
	fossil RD&D	"How has your fossil RD&D investment volume changed in the last five years (2005-2009) compared to the previous five year period (2000-2004)?"	{-2,...,2}	0.67	0.99	0.42	1.20	0.52	1.12
	non-fossil RD&D	"How has your non-fossil RD&D investment volume changed in the last five years (2005-2009) compared to the previous five year period (2000-2004)?"	{-2,...,2}	0.84	0.82	1.02	0.84	0.99	0.84
climate policy	perception of ETS 1&2	"To what extent is your company negatively or positively affected by the EU emissions trading in the period 2005-2012?"	{-2,...,2}	-0.02	0.82	0.29	0.78	0.19	0.81
	perception of ETS 3	"To what extent is your company negatively or positively affected by the EU emissions trading in the period 2013-2020?"	{-2,...,2}	-0.54	1.02	0.42	0.82	0.11	0.99
	perception of LTT	"To what extent is your company negatively or positively affected by long-term European and global reduction targets for greenhouse gases as in 2020?"	{-2,...,2}	-0.68	1.02	0.85	0.88	0.35	1.17
	perception of LTT as issue	*absolute value of the answer to the previous question*	{0,1,2}	1.02	0.67	0.98	0.73	0.99	0.71
cognition of context	perception of technology-push policies	"To what extent is your company negatively or positively affected by EU & national policies promoting R&D and innovation over the last five years (2005-2009)?"	{-2,...,2}	-0.02	0.66	0.57	0.85	0.38	0.83
	perception of RET demand-pull policies	"To what extent is your company negatively or positively affected by the policy framework regarding renewable energies over the last five years (2005-2009)?"	{-2,...,2}	0.58	1.00	1.17	0.96	0.98	1.01
	perception of fuel price	"To what extent is your company negatively or positively affected by fuel price development over the last five years (2005-2009)?"	{-2,...,2}	-1.03	0.87	0.25	1.05	-0.16	1.16
	perception of electricity price	"To what extent is your company negatively or positively affected by electricity price development over the last five years (2005-2009)?"	{-2,...,2}	-0.31	1.18	0.44	1.01	0.20	1.12
	perception of public acceptance of coal	"To what extent is your company negatively or positively affected by the public acceptance for hard coal and lignite over the last five years (2005-2009)?"	{-2,...,2}	-0.59	0.91	-0.01	1.00	-0.20	1.01
firm characteristics	value chain position	*dummy variable (1: PG, 2: TP)*	{1,2}	1.00	0.00	2.00	0.00	1.68	0.47
	fossil share	"What is the percentage of fossil fuel based generation in your total electricity generation?"	[0,100]	81.3	30.4	13.6	27.2	35.4	42.4
	need for replacement	"With hindsight to 2005: How do you judge the need to replace or extend the generation portfolio?" *(1: no need…5: high need)*	{1,2,3,4,5}	3.10	1.25	-	-	-	-
	technological capabilities	*standardized and factorised share of R&D expenditure to sales and of R&D staff to total employees*	(-∞,∞)	0.00	1.00	0.00	0.99	0.00	1.00
	size	"What was the total company turnover in 2008?" *(1: < 2 million €, ... 6: > 5 billion €)*	{1,2,3,4,5,6}	3.40	1.43	2.51	1.46	2.80	1.51

Table A3: Correlations (Kendall's tau) for the adoption (top, PG, only) and RD&D models (bottom, PG and TP performing R&D)

** Significant at the p<1% level. * Significant at the p<5% level

			1	2	3	4	5	6	7	8	9	10	11	12	13
1		adoption, in total	1												
2		adoption, fossil	.591**	1											
3		adoption, non-fossil	.350**	0.122	1										
4	perception of	EU ETS 1&2	0.169	0.14	0.005	1									
5		EU ETS 3	-0.138	-0.104	-0.119	.336**	1								
6		LTT (absolute)	0.185	0.052	.230*	0.004	-.391**	1							
7		RET demand-pull policies	.297**	0.092	.361**	0.056	0.091	0.079	1						
8		fuel prices	0.13	0.197	-0.03	0.037	0.14	-0.17	0.106	1					
9		electricity prices	.233*	0.137	0.102	0.108	-0.004	0.022	0.2	.474**	1				
10		public acceptance for coal	-0.027	0.016	-0.02	-0.122	0.109	-0.105	0.028	-0.044	-0.007	1			
11		share fossil	-.199*	-.215*	-.259*	-0.011	-0.19	0.04	-.300**	-0.165	-0.194	.232*	1		
12		need to replace/extend capacity	.333**	0.173	0.164	0	0.057	-0.148	0.104	0.178	0.053	-0.011	-0.141	1	
13		size	.382**	.401**	0.134	-0.003	-0.031	-0.024	0.076	.277**	0.147	-0.153	-.345**	0.15	1

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1		RD&D, in total	1														
2		RD&D, fossil	.480**	1													
3		RD&D, non-fossil	.681**	0.123	1												
4	perception of	EU ETS 1&2	.155*	0.142	.201*	1											
5		EU ETS 3	0.122	-0.084	0.097	.607**	1										
6		LTT (absolute)	.310**	0.129	.305**	.189**	0.114	1									
7		technology push policies	.235**	0.175	.289**	.121*	.208**	0.098	1								
8		RET demand-pull policies	.236**	-0.12	.231**	.203**	.281**	.212**	.429**	1							
9		fuel prices	0.087	-0.024	0.12	.200**	.344**	0.059	.254**	.325**	1						
10		electricity prices	.221**	0.08	.296**	.232**	.234**	0.111	.271**	.287**	.503**	1					
11		public acceptance for coal	.232**	0.105	.254**	0.021	.185**	0.045	.214**	.236**	.205**	.214**	1				
12		value chain position	0.095	-0.03	0.119	.155*	.409**	-0.039	.335**	.290**	.476**	.258**	.245**	1			
13		share fossil	-0.061	.303*	-.180*	-.206**	-.379**	-0.025	-.301**	-.359**	-.420**	-.281**	-.170**	-.632**	1		
14		technological capabilities	.235**	0.038	.304**	.112*	0.109	0.095	.169**	.130*	0.072	.115*	0.046	-0.023	-0.06	1	
15		size	0.091	0.213	0.009	-0.026	-0.043	.133*	-0.011	0.01	-0.084	-0.047	-0.05	-.262**	.162**	.108*	1

Annex I

Paper 6

Decarbonising the power sector via technological change – differing contributions from heterogeneous firms

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- Under review for Energy Policy -

Abstract

In the power sector, technological change is a key lever to address the decarbonisation needed to avoid dangerous climate change. Policy makers aim to accelerate and redirect technological by targeting relevant firms via climate policy, e.g. the EU ETS, and climate-relevant technology policies, e.g. feed-in tariffs. Changes in firm's behaviour, i.e. their R&D and diffusion activities, are at the heart of technological change. However, firms are heterogeneous actors with varying attributes which perceive policy differently. Hence, they can be expected to react very heterogeneously to these new policies. Based on an original dataset of 201 firms, we perform a cluster analysis grouping firms along their R&D and diffusion activity changes. We then compare these clusters with regards to the characteristics of the contained firms. Our analysis results in seven clusters showing very diverse contributions to low-carbon technological change, suggesting potential for policy to become more effective. A comparison of the firms' characteristics allows us to derive indicative recommendations on how to adjust the policy mix in order to induce contributions from most firms in the power sector.

Keywords: technological change; climate-relevant policy; power sector

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1. Introduction

Climate change resulting from anthropogenic greenhouse gas (GHG) emissions is a major challenge for societies worldwide (IPCC, 2007a). While the power sector is one of the main sources of GHG emissions, it also has high decarbonisation potential: The International Energy Agency (2010) assumes that it could contribute over 40% of the 21 billion tonnes CO_2e emission abatements that are needed by 2035 to achieve the 450ppm target[1]. Besides unlocking the large demand-side efficiency potential, the development and diffusion of renewable energy technologies (RET), carbon capture and storage (CCS) and highly efficient fossil fuel power plants are key levers for achieving these emission cuts[2]. While the IEA estimates that the specific CO2 emissions of power generation will drop to a quarter of today's value by 2035, other scenarios are even more aggressive (IPCC, 2011; Krey and Clarke, 2011 provide recent Scenario overviews). Notwithstanding the differences in the assumptions of each scenario, they all conclude that technological change (TC) must be accelerated and redirected onto a low-carbon pathway if the 450 ppm target is to be achieved. This has to happen in a timely manner, given that global emissions continue to rise strongly (ESRL, 2010). In spite of the fact that low-carbon TC is the most important factor for achieving the 450 ppm target, it is not yet well understood (Pizer and Popp, 2008). This paper focuses on the role of policy, which aims at the decarbonisation of the power sector, in inducing an acceleration and redirection of technological change (TC).

The European Union (EU) and its member states have introduced and reinforced climate policy and climate-relevant technology policies (del Río, 2009; Rogge et al., 2011b; Sijm, 2005). The few studies to date that have analysed the effects of these new policies (for an overview over the role of the EU ETS see e.g., Zhang and Wei, 2010) on low-carbon TC mostly stem from the neoclassical environmental economic school or from evolutionary innovation studies. While environmental economists look at the role of policy for inducing innovation at a sectoral level, assuming rational firm behaviour (for a recent overview see e.g., Popp et al., 2010), evolutionary scholars stress the role of the tacitness of technology and firm heterogeneity (Dosi, 1997; Nelson and Winter, 1982). They argue that in order to study the role of policy in the acceleration and redirection of TC, it is vital to look at the level at

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[1] A 2 °C warming above the pre-industrial temperature is commonly taken as the approximate threshold for dangerous interference with the climate system. Meeting the 450ppm target results in a probability of 25 to 75% of not exceeding the target (IPCC, 2007b; Knutti and Hegerl, 2008).

[2] While some scenarios expect a rapid growth of nuclear others do not. The role of nuclear power is highly debated, particularly following the Fukushima accident in March 2011.

which innovation takes place: the firm level[3].

TC encompasses three interacting stages, from invention via innovation to the diffusion of new technology (Schumpeter, 1942). As such it is a non-linear process over time (Dosi, 1997; Silverberg et al., 1988), which is embedded in a historic and institutional context (Dosi, 1988; Malerba et al., 2001). Firms contribute to technological change via two activities: research and development (R&D) and diffusion activities. The former refers to activities from basic laboratory research to the development of marketable products (Gatignon et al., 2002) and encompasses the first two stages of Schumpeter's definition of TC (invention and innovation). The latter encompasses the production and sale of new technologies by producers and the adoption of these technologies by users (Ashford, 1993; Gort and Konakayama, 1982) and refers to the last stage of Schumpeter's definition (diffusion).

Thus far, empirical studies looking at the effect of climate and climate-relevant technology policies on TC using firm level data are either of qualitative nature (e.g., Cames, 2010; Ikkatai et al., 2008; Rogge et al., 2011b), focus on a single innovative activity i.e., R&D or diffusion (e.g., Laurikka and Koljonen, 2006), and/or analyse both activities separately (e.g., Rogge et al., 2011a; Schmidt et al., 2011). However, firms typically consider both activities simultaneously in order to arrive at a consistent investment decision (Lavie et al., 2010; March, 1991). Hence, there is a lack of quantitative analyses looking at firms' integral *behaviour*, i.e., the totality of a firm's decisions on how to devote resources to the R&D *and* diffusion activities of different technologies.

Of particular interest for policymakers is how firms adjust behaviour in new regulatory environments. Such information may be used to answer the question of whether readjustments of the policy mix are needed. Firms are expected to change their behaviour in different ways; i.e., a population of firms is expected to exhibit *behavioural heterogeneity* (Nelson, 1991). Observing behavioural heterogeneity, i.e., whether firms change their behaviour to which extent and how, can provide quick feedback on the state of the acceleration and redirection of TC. The behavioural heterogeneity is explained by the different characteristics of the firms, i.e., their *characteristic heterogeneity* (Nelson, 1991). Should the findings on the behavioural heterogeneity show a need for policy readjustments, information about the characteristic heterogeneity of firms is also valuable for policy makers. Knowing which kind of firms follow a certain pattern of behavioural change allows for deriving policy recommendations for specific actors and thereby addressing the question of how to adjust the policy mix. By

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[3] While also other actors are important sources of innovation (e.g., universities), the scale of emission abatement needed requires a strong contribution from the private sector.

covering both aspects, the behavioural and the characteristic heterogeneity, we address the following research question: *How do firms with diverse characteristics differ regarding their contributions to low-carbon technological change in the power sector?*

In order to address this question, we analyse original survey data on power generators and power generation technology providers in seven European countries. First, we perform a cluster analysis to identify different patterns of corporate *behaviour changes*. Second, we compare these clusters regarding observable *firm characteristics*. The paper is structured as follows. We develop a research framework in Section 2, explaining our variables and highlighting both important aspects of the heterogeneity of firms in the power sector. We then present the surveyed variables, provide details about the sample of firms and explain the statistical methodologies applied in Section 3. From the results portrayed in Section 4, we derive recommendations on whether and how to improve the existing policy mix in order to better target heterogeneous firms in Section 5. The paper is concluded in Section 6.

2. Framework

TC can be analysed on different levels. While most environmental economists analyse the role of policy for TC on a sectoral level (e.g., Betz and Owen, 2010; Weber and Neuhoff, 2010), evolutionary innovation scholars inscribe a central role to the actors involved in innovation, e.g., firms, stressing their heterogeneity (Dosi, 1997). We follow this tradition and, rather than analysing the role of the policy on the sectoral level (compare the dashed arrow in Figure 1), descend to the firm level. The findings generated at this level allow us to draw initial conclusions on the acceleration and redirection of TC at the sectoral level. Figure 1 depicts our framework and can be summarised as follows. Various policy elements affect firms with heterogeneous attributes differently. Consequently, their reactions in the form of behaviour change can vary strongly. This in turn is likely to affect the acceleration and redirection of TC. In the following we explain our framework, starting with the acceleration and redirection of technological change and moving in an anti-clockwise direction.

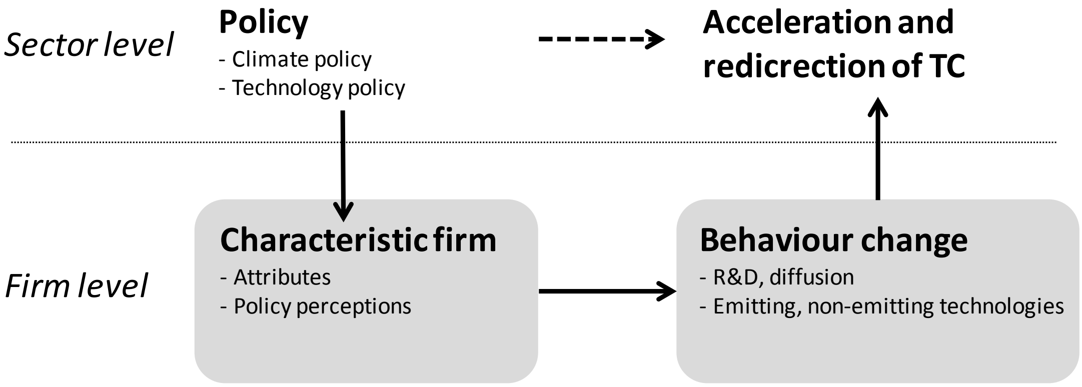

Figure 1: Framework for analysing the role of firm heterogeneity in the effects of policy on technological change. The grey boxes show the two analytical steps we perform in this study.

Acceleration and redirection of technological change

For an acceleration and/or redirection of technological change in a sector, the relevant actors have to alter their behaviour (Archibugi and Planta, 1996; Peneder, 2010; Schumpeter, 1912). For instance, increased R&D by a firm can lead to an improvement in technology and thereby enhance its competitiveness against rival technologies (Nelson and Winter, 1982; Suarez, 2004). If the R&D and diffusion lead to a change in the sectoral structure, TC at the sector level has taken place. Therefore, in order to accelerate and redirect TC it is necessary that the behaviour of individual firms is altered in a way that supports low-carbon TC. However, due to long lead times in the power sector, caused, inter alia, by the construction time of power plants (Roques et al., 2008), the measurability of TC at the sector-level is delayed (Cames, 2010). Therefore, analysing changes in the behaviour of firms can serve as an early indicator of the acceleration and redirection of TC.

Policy

The policy mix aiming at low-carbon TC in the power sector can be differentiated into climate policy and technology policies (e.g., Azar and Sandén, 2011; Jaffe et al., 2005). Climate policy alters the competitiveness of technologies by putting a price on carbon, such as through a carbon tax or an emission cap and trade system. Emitting technologies are fined, whereas non-emitting technologies are not directly affected but may benefit from increased electricity prices. Nevertheless, climate policy is regarded as technology neutral as emissions are targeted independently from the source (Azar and Sandén, 2011). In the European Union it is operationalised via the EU ETS (European Commission, 2005, 2010) and emission reduction targets, which have been shown to be an important element of the climate policy mix (Rogge and Hoffmann, 2010). Besides these technology-neutral policies, technology policies which, as the name implies, target specific technologies in different ways, are an important element in the policy mix. Among technology policies, technology-push and technology-specific demand-pull instruments can be distinguished (Rennings, 2000; Taylor, 2008). The former are designed to induce or directly fund private R&D in order to improve technologies in important performance dimensions (Nemet, 2009) - examples are the R&D subsidies devoted to CCS and RET by the EU (European Commission, 2009). The latter create demand for technologies whose competitiveness is currently inferior to other technologies but which have significant cost reduction potential (Taylor, 2008). In the power sector, preferential feed-in tariffs or quotas for renewable energy technologies are instruments which are often utilised (Mendonça, 2010; Ringel, 2006).

Characteristic heterogeneity: attributes and policy perceptions

The policies outlined above impact on a population of heterogeneous firms in the power sector. The characteristic heterogeneity of firms within one sector refers to a firm’s structure and capabilities (Nelson, 1991). In the power sector and for the purpose of this study the heterogeneity of firms regarding structure and capabilities can be expressed by four attributes (Panda and Ramanathan, 1996; Rogge et al., 2011b): the size, the value chain position, the technology portfolio and the technological capabilities of a firm. Figure 2 depicts some examples of relevant firms in the power sector portrayed along these differences.

The first characteristic is the *size* of a firm, which is assumed to be positively correlated to its resource slack (Dimick and Murray, 1978). Resource slack is defined as “a cushion of actual or potential resources [...] which allows an organisation to adapt successfully to [...] external pressures [...]” (Bourgeois, 1981)., Larger firms can therefore react differently from smaller firms during changes in their business environment (Cyert and March, 2005).

Second, regarding the *value chain position* of the firms (Rogge et al., 2011b), we differentiate between technology users and technology producers. In the power sector, the term *technology user* refers to power generators who select between alternative electricity generation technologies when building new capacity. Above that, users are the firms directly regulated by the EU ETS. The term *technology producer* refers to power generation equipment suppliers. Third, firms’ *technology portfolios* can differ significantly as firms can either be active in one or several technologies, each of which can be GHG emitting or non-emitting. In the power sector, GHG emitting technologies are based on the combustion of fossil fuels, whereas non-emitting technologies use other sources of energy. We therefore differentiate between *fossil* and *non-fossil* technologies. The composition of the portfolio thus determines the emission intensity of the portfolio (Rogge et al., 2011b) and the impact of a policy on a firm (see below). Finally, a firm can have high or low *technological capabilities*, i.e. “patents protected by law, technological knowledge, and production skills that are valuable and difficult to imitate by competitors” (Lee et al., 2001, p. 618). It has been shown that firms with higher technological capabilities tend to react with more innovation to external stimuli, such as the introduction of policy (Rosenberg, 1974).

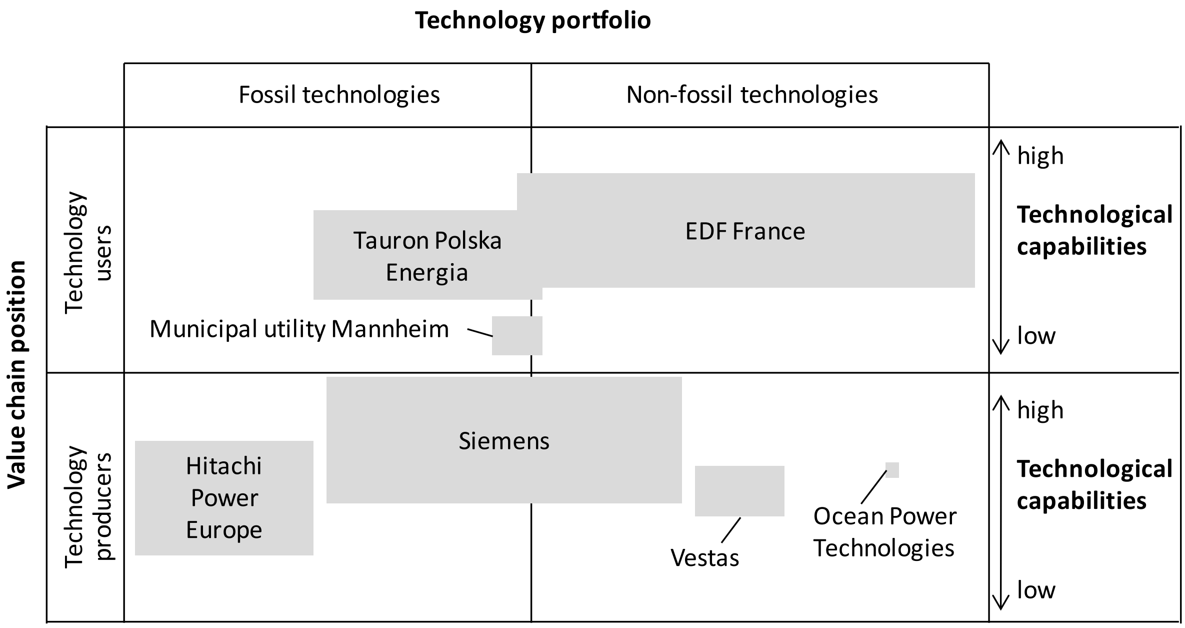

Figure 2: The four heterogeneity attributes and example firms. The size of the firm is represented by the size of the grey squares. The figure is not to scale but sketches the very large heterogeneity of some example firms. These examples were picked irrespective of their (anonymous) participation in the survey.

Organisational theory scholars argue that besides their attributes corporate perceptions are essential determinants of firms' behaviour changes (Bansal, 2003; Buysse and Verbeke, 2003; Dutton and Jackson, 1987). Each individual firm perceives its business environment and changes therein (e.g., via the introduction of climate policy) differently (Dosi et al., 1997). Firms can perceive such changes neutrally or as opportunities or threats to different degrees (Barr et al., 1992; Dutton and Jackson, 1987). Besides their heterogeneous attributes, firms' "limited understanding [...] of the environment in which they are embedded" leads to different perceptions (Dosi et al., 1997, P. 1540). We summarize the attributes and policy perceptions under the term *characteristic heterogeneity*.

Behavioural heterogeneity: changes in R&D and diffusion activities

Firms with varying attributes and policy perceptions are expected to react differently to changes in their business environment regarding their behaviour (Nelson, 1991). This means that firms can decide to alter the existing allocation of internal resources to the different innovative activities, i.e., R&D and diffusion, of different technologies (Oltra and Saint Jean, 2005). R&D refers to the continuum from basic laboratory research potentially leading to radical breakthroughs (e.g. through new materials for turbines) to applied development resulting in the better performance of products (Gatignon et al., 2002). Besides few large technology users it is mainly technology producers who create novelty via R&D in the ‘supplier dominated’ power sector (Cames, 2010; Pavitt, 1984). It is therefore important to not only include the firms that are causing the emissions during the usage phase but also the firms positioned one step up in the value chain. Diffusion refers to adoption decisions on the user side (Ashford, 1993) and production and sales activities on the producer side (Gort and Konakayama, 1982). With their behaviour changes, firms can contribute to the acceleration and redirection of TC. Hence, looking for different patterns of behavioural change is the first step towards answering our research question. In order to better understand which firms follow which specific pattern, we also analyse their characteristics.

3. Methodology

3.1 Survey and sample

Our data stems from an original survey conducted in November and December 2009 amongst power generators and technology providers from seven EU countries, namely Germany, France, Italy, Poland, Slovakia and Spain plus - in the case of the technology providers - the UK. Subsequent to a series of pre-tests in Austria which served to improve our survey, the final survey was translated in each respective language and a reverse translation was independently conducted in order to guarantee equality in meaning. In order to identify the most suitable respondent each firm in the sample was contacted by phone. To ensure the survey was answered by the senior manager identified, a letter and email with an individual access code was then sent. Follow-up calls were made to increase the response rate. In the following we describe how we operationalised the variables set out above.

The analyses performed in this study are based on the answers of 201 firms, 65 power generators and 136 technology providers. This represents a response rate of 13.1% and 12.5% of the population of 496 power generators and 1088 technology providers respectively. The population of power generators in each country was identified based on the EU's Community Independent Transaction Log (CITL) comprising all firms which fall under the EU ETS. The technology provider population in each country was identified on the basis of the KKS power plant classification system of VGB Powertech, the respective European industrial activity classifications (NACE Rev.2) and the firm registry Amadeus. Table A1 (see Annex) shows the respondents’ countries of origin. As a result and in contrast to most other survey-based studies on the power sector, our dataset also includes firms which are not publically listed. Regarding power generators, the strong bias towards Germany is partially based on its very high number of (small) firms compared to the other countries. A similar trend can be observed in the producer sample. With the exception of France and the UK - which are underrepresented - these numbers provide representative drawings of the entire population of technology providers. Of the power generators, 76% have undertaken adoption measures (i.e., invested in new plants) and 37% have conducted R&D within the last ten years, which is our time horizon for innovation observations. As expected, the number of producers undertaking R&D activities is higher, namely 69%. The remaining 31% focus on technology assembly and do not invest in formal R&D. Table A2 (Annex) summarizes the descriptive statistics of the entire sample.

3.2 Variables

Behaviour change

In order to capture behaviour changes, we distinguish between R&D and diffusion for both fossil (lignite, hard coal, gas, oil) and non-fossil (nuclear, renewable) technologies[4], resulting in four variables. We surveyed the four variables by asking how the monetary volumes of R&D investments and investments in new plants (power generators) or sales (technology providers) have changed in the last five years (2005-2009), since climate policy was introduced, compared to the previous five years (2000-2004, this period thus serves as benchmark.) The answer categories of the five-point Likert scale ranged from “dropped sharply” (-2) via “no change” (0) to “rose sharply” (+2). This is of course a relatively rough gauge, however firms are typically unwilling to report exact investments.

Climate and technology policy

Five policy variables are taken into account, each representing policies that aim to induce a low-carbon transition in the power sector. The European Union’s *Emission Trading System (ETS)* is considered via two variables as we distinguish the more short-term and lax *phases 1 and 2* (from 2005 to 2012) from the medium-term and more stringent *phase 3* (from 2013 to 2020). In the first two phases, over-allocations of emission rights were common. This changes in phase three when a rising share of emission rights will have to be auctioned (Betz et al., 2006; Ellerman and Buchner, 2007). Furthermore we consider *long-term targets (LTT)*, which represent European and global GHG emission reduction targets for 2020. Besides climate policy, two types of technology policy instruments were considered: *technology push* (such as R&D subsidies) and *technology-specific demand-pull* measures (such as preferential feed-in tariffs for RET).

We queried the perception of each policy variable again via a five-point Likert scale ranging from “very negatively affected” via “not affected” to “very positively affected” (Barr et al., 1992; Dutton and Jackson, 1987).

Firms’ attributes

As mentioned above, we use four variables to describe the firms’ structure and capabilities. The *value chain position* is represented via a dummy variable, which ascribes the value 1 to

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[4] The two groups of fossil and non-fossil technologies are very dissimilar regarding their specific GHG emissions. We included technologies specific to Combined Heat and Power (CHP) and Carbon Capture and Storage (CCS) in the fossil technology group. Given that large specific emission differences occur between fossil technologies, the aggregation of fossil technologies is obviously a simplification. This simplification is necessary to enable the cluster analysis.

power generators and 2 to technology providers. The *size* of the firm is expressed by its turnover. We surveyed the turnover via exponentially rising answer categories. The *share of fossil technologies* in a firm's generation portfolio (power generators) or its sales (technology providers) as of 2009 describes its technology portfolio and can range from 0 to 100%. The *technological capabilities* were measured via two factorised[5] items, the percentage of R&D expenses per turnover and the percentage of R&D employees per overall staff. As for all supplier dominated sectors, in the power sector the rate of R&D activity differs strongly between users and producers of technology and thus correlates with the value chain step dummy. Hence, we standardized the variable per value chain step via z-scores before merging the sub-samples.

3.3 Statistical Methodology

Statistically we proceeded in two steps. First, in order to identify different patterns of behavioural change of the firms in the sample, a cluster analysis based on the four variables describing the changes in behaviour was performed. For the cluster analysis we chose a two-step approach. To this end, we conducted a hierarchical cluster analysis based on Ward's method in order to identify the optimal number of clusters based on the elbow criterion. Based on these results, we then performed a non-hierarchical K-means analysis to allot the 201 firms to the respective clusters on the basis of their behaviour changes (Hair et al., 2006).

Second, in order to compare the clusters along their characteristics we used non-parametric tests for each variable. We decided to use these tests as they can also be applied to samples whose variables are not normally distributed. First we tested whether there are significant differences between any of the clusters via Kruskal-Wallis tests (Field, 2009; Hair et al., 2006). The Kruskal-Wallis test is also applied to the behaviour change variables in order to check whether the clusters differ significantly regarding these variables. Second, we conduct Mann-Whitney tests in order to compare clusters in a pairwise manner (Field, 2009; Hair et al., 2006). As each test is conducted on the same statistical sample, the familywise error rate leads to an alpha inflation, making a Bonferroni correction indispensable (Field, 2009). As conducting too many Bonferroni-corrected tests lead to a restrictive significance level (Field, 2009), we limited the number of pairwise tests to five (see section 4.2).

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[5] The factor analysis fulfils the Kaiser criterion (Kaiser, 1960).

4. Results

The results section is split into three parts. First, we report the statistical results of both the cluster analysis revealing the behavioural heterogeneity and the comparison of the clusters along their characteristics. Second, we describe each cluster along its behavioural and characteristic heterogeneity. Third, we summarize our findings and give an overview in Table 3.

4.1 Statistical results

Behavioural heterogeneity

Our analysis resulted in seven clusters[6]. Table 1 shows the respective clusters, their centres (means) with respect to the changes in R&D and diffusion activity of fossil and non-fossil technologies as well as their size in absolute and relative terms. The names of the clusters are chosen to summarize their behaviour change. Generally three groups can be identified (compare the three shades of grey in Table 1).

Table 1: Changes in behaviour – cluster centres and size

			BAU	Fossil Diffusion	Clean Focus	Overall Diffusion	Overall Innovation	Clean Shift	Fossil Exit
Cluster Centers	R&D	non-fossil	0.15	0.07	1.11	0.05	1.36	1.50	-0.10
		fossil	0.06	0.27	0.00	0.15	1.25	-1.90	0.00
	Diffusion	non-fossil	0.17	-0.20	1.78	1.56	0.97	1.52	0.27
		fossil	0.02	1.67	0.00	1.43	0.77	-0.40	-1.55
Number of companies			80	15	59	17	15	5	10
% of companies			39.80%	7.50%	29.40%	8.50%	7.50%	2.50%	5.00%

The cluster centres can theoretically vary from -2 via 0 to +2, indicating whether the respective activity was strongly decreased, kept constant or strongly increased.

First, almost 40% of the firms (*Business as usual, BAU*) show no major changes regarding their behaviour. Second, 15 firms (*fossil diffusion*) contribute to increased fossil technology diffusion (1.67 out of a maximum possible increase of 2) and thus play a rather controversial role in the low-carbon TC. Third, more than 50% of the firms contribute to low-carbon TC but to varying degrees and in different ways. This indicates that on the one hand some

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[6] The Kruskal-Wallis tests rejected the null hypothesis that all clusters do not differ significantly regarding each variable measuring innovation behaviour change.

acceleration and redirection of TC is taking place in the sector, but that on the other hand the contribution of many firms is limited and of some might even be controversial.

Characteristic heterogeneity

The results of the cluster comparison regarding the four attributes and five policy perceptions of the firms are summarised in Table 2. This shows the mean and standard deviation (std d) of the respective variables as well as the cluster size. For all variables, the Kruskal-Wallis tests resulted in a rejection of the null-hypothesis. Hence, at least one cluster differs significantly (at p<5%) on each variable from at least one other cluster. In order to better understand the differences between the clusters, we used the *BAU* cluster – the biggest cluster which does not show major changes in behaviour – as a reference case and compared each cluster against it to find significant differences (at p<5%) via Mann-Whitney tests, adjusting the significance level with Bonferroni corrections, as mentioned above. In Table 2 the means of the variables significantly different to BAU are underlined[7].

Table 2: Comparison of the clusters' characteristics, i.e., attributes and policy perceptions

		BAU		Fossil Diffusion		Clean Focus		Overall Diffusion		Overall Innovation		Clean Shift		Fossil Exit	
		mean	std d	mean	std d	mean	std d	mean	std d	mean	std d	mean	std d	mean	std d
Attributes	Value Chain Pos*	1.70	.46	1.27	.46	1.93	.25	1.47	.51	1.60	.51	1.80	.45	1.00	.00
	Size (turnover)	2.59	1.52	3.09	1.39	2.65	1.40	3.56	1.34	3.87	1.73	2.60	1.52	2.14	1.24
	Share Fossil (in %)	38.10	42.32	79.97	35.46	6.90	22.65	48.24	40.00	44.67	35.76	.00	.00	98.00	4.22
	Tech Capabilities	.06	1.13	-.27	.43	-.09	.53	-.13	.72	.38	1.27	.80	1.15	-.30	.16
Policy Perception	ETS 1 & 2	.02	.76	.20	.86	.43	.79	.12	.93	.33	.62	.80	.84	-.30	.82
	ETS 3	.07	.80	-.53	.83	.47	.95	-.29	1.31	.20	1.01	.80	.84	-.50	1.35
	LTT	.24	.96	-.73	.80	1.06	1.00	-.30	1.30	.60	1.12	1.20	.84	-1.00	.94
	Tech.-push policy	.35	.88	-.06	.60	.67	.74	.06	.75	.74	.59	-.19	1.26	-.15	.75
	RET-pull policy	.78	1.04	.13	.99	1.51	.70	1.06	.75	1.13	1.06	1.43	.52	.20	1.14
Number of companies		80		15		59		17		15		5		10	
% of companies		39.80%		7.50%		29.40%		8.50%		7.50%		2.50%		5.00%	

* 1: Power generators (users), 2: Technology providers (producers)

Several clusters differ strongly regarding both the firms' attributes and their policy perceptions. While the BAU cluster seems to contain very heterogeneous firms (the variance of the distribution is quite high), other clusters show strong peculiarities, e.g., the fact that all

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[7] The small cluster size of *clean shift* prevented the inclusion of this cluster in the Mann-Whitney tests.

firms in the *fossil exit* cluster are power generators. In the next section, we will show that firms' heterogeneity of attributes and policy perceptions can be linked - to some extent - to their dissimilar behaviour changes. Therefore, in order to better understand the role of firm heterogeneity for the role of policy for TC, we now turn to each individual cluster and discuss both the behavioural and characteristic aspects of heterogeneity.

4.2 Description of each cluster with regards to both aspects of heterogeneity

In the following we derive each cluster's individual contribution to the acceleration and redirection of TC from the observed behaviour changes and the cluster size. We then discuss the role of characteristic heterogeneity and – where applicable – highlight significant differences to the BAU cluster.

Business as usual (BAU) Cluster

The firms in the *BAU* cluster did not change their behaviour and hence maintain a more or less constant speed and direction of TC. The fact that almost 40% of firms exhibit such behaviour points to considerable inertia within the sector.

The BAU cluster encompasses one third of power generators and two thirds of technology providers. They are medium sized and have mixed portfolios (with a high variance) with moderate technological capabilities (but also exhibit a large variance). Their perception of policy seems to be relatively neutral, with RET pull policies being perceived as opportunity (again showing a high variance). To summarise, the heterogeneity of firms within this cluster is very high, indicating that firms which follow this pattern of no considerable behaviour changes vary considerably.

Fossil diffusion Cluster

While the *BAU* cluster contributed very little or not at all to an acceleration and redirection of TC the 15 firms in the *fossil diffusion* cluster do so, but in a fossil fuel-based direction. The only behavioural change identified is their strong increase in fossil diffusion activities. As current fossil technologies' emission reduction potential is rather limited, and the increased diffusion of these technologies at present represents future GHG emissions for at least the typical 25 year minimum lifetime of fossil power plants (Roques et al., 2008), these firms counteracted low-carbon TC.

Firms in the *fossil diffusion* cluster show several peculiarities. About 70% are power generators, which is a significantly higher rate than in the *BAU* cluster. They are relatively large in size and their portfolios already tend to be dominated by fossil technologies –

significantly more than those of the firms in the *BAU* cluster. Their technological capabilities are rather low on average, and their perception of climate policy is slightly positive regarding ETS 1&2 and negative (significantly more than that of *BAU* firms) regarding ETS 3 and LTT. Technology policies are perceived relatively neutrally on average (but variant).

Clean focus Cluster

Of the roughly 50% of firms contributing to low-carbon TC, the clean focus cluster represents the biggest group. These firms strongly increased R&D and diffusion activities in the non-fossil direction while keeping their innovation activities in fossil technologies constant. They thereby contributed to both an acceleration and redirection of TC in the low-carbon direction.

Almost all firms in the *clean focus* cluster are technology providers (significantly higher share than in the *BAU* cluster). The firm size is rather small (but has a high variance) and the share of fossil technologies in their portfolios is low (significantly lower than of the *BAU* cluster). Their technological capabilities are close to the average of all firms. The three climate policy elements are perceived as an opportunity to a significantly higher extent than in the *BAU* cluster. Technology-push and RET-pull policies are also seen positively, with the latter significantly more so than by the firms in the *BAU* cluster. The cluster shows the most positive perception of RET pull policies (however not significantly higher than the *BAU* cluster).

Overall diffusion Cluster

These 17 firms contributed to a mere acceleration of TC. They strongly increased their technology diffusion activities in both technologies while keeping their R&D activities constant. Thus, their contribution to low-carbon TC in the sector was limited[8].

The cluster is comprised of power generators and technology providers half-and-half. While they are large in size and have mixed portfolios, their technological capabilities are moderate (with a high variance). Their policy perception is tends towards neutral (but is highly variant), except for RET pull policies which are seen as an opportunity. Significant differences to the BAU were neither detected for the attributes nor for the policy perceptions.

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[8] While an increased diffusion of non-fossil technologies leads to a decarbonisation of the sector, specific GHG emission reductions via the diffusion of currently available fossil technologies are rather limited and create long-term lock-ins (see above).

Overall innovation Cluster

Similarly to the above cluster, these 15 firms contributed to an acceleration of TC, with the addition that they simultaneously increased R&D *and* diffusion activities in both technologies. While the increased activities in non-fossil technologies are a certain contribution to low-carbon TC, the increased diffusion of fossil technologies is controversial (see above). To which extent the increased fossil R&D activities represent a positive contribution depends on whether it results in drastic specific GHG emission reductions of the respective technologies.

About one third of the firms are power generators, two thirds technology providers. They are the largest firms on average – significantly larger than the firms in the *BAU* cluster. While their portfolios are mixed (and variant), their technological capabilities are higher than average (but also highly variant). They perceive climate policy as slightly positive. Technology policy is seen as an opportunity, with R&D push policies reaching the highest value of all clusters. Significant differences to the BAU cluster were not detected regarding their policy perceptions.

Clean Shift Cluster

Similarly to the *clean focus* cluster, these five firms strongly increased non-fossil R&D and diffusion activities. However, they went one step further by drastically decreasing their innovative activities in fossil technologies. In doing so they contributed to a redirection of TC in the low-carbon direction. However, due to the small size of the cluster and the firms (see below) their contribution was limited.

The *clean shift* cluster is dominated by smaller-sized technology providers (these show a high variance however). Their shift away from fossil technologies resulted in portfolios constituted entirely of non-fossil technologies. Their technological capabilities are the highest of all clusters (though showing a high variance). They are the cluster which perceives all three climate policy elements most positively. Technology push policy has a slightly negative mean with a high variance. RET policies are also seen as an opportunity.

Fossil Exit Cluster

Like the cluster above, the ten firms in the *fossil exit* cluster contributed to a mere redirection of TC in the low-carbon direction. Yet, they showed a rather hesitant or passive behaviour change. They strongly reduced their fossil diffusion activities but kept all other activities relatively constant.

The *fossil exit* cluster is entirely made up of power generators (i.e., significantly different from the *BAU* cluster). The average firm size of the *fossil exit* cluster is the lowest of all clusters (but exhibits a relatively high variance). Despite their fossil exit strategy, the firms of this cluster still have very high shares of fossil technologies in their portfolios, significantly higher than firms in the *BAU* cluster. On average, the firms in the cluster exhibit relatively low technological capabilities. Their perception of climate policy is throughout negative (but relatively variant), with LTT reaching the most negative value of all clusters and being significantly more negative than that of the BAU cluster. Technology policy is seen as rather neutral (with a high variance especially for RET pull).

4.3 Summary of results

Our findings illustrate the strong role of firm heterogeneity when analysing policy induced technological change in the power sector. Many firms do contribute to the acceleration and redirection of TC but in a very heterogeneous manner and often also differ regarding their characteristics. One important characteristic which is often overlooked is the value chain position as most studies focus on a single value chain step which is appropriate in other industries (Cames, 2010). In order to highlight the importance of this aspect Figure 3 shows how the firms of the two different value chain steps are distributed to the clusters.

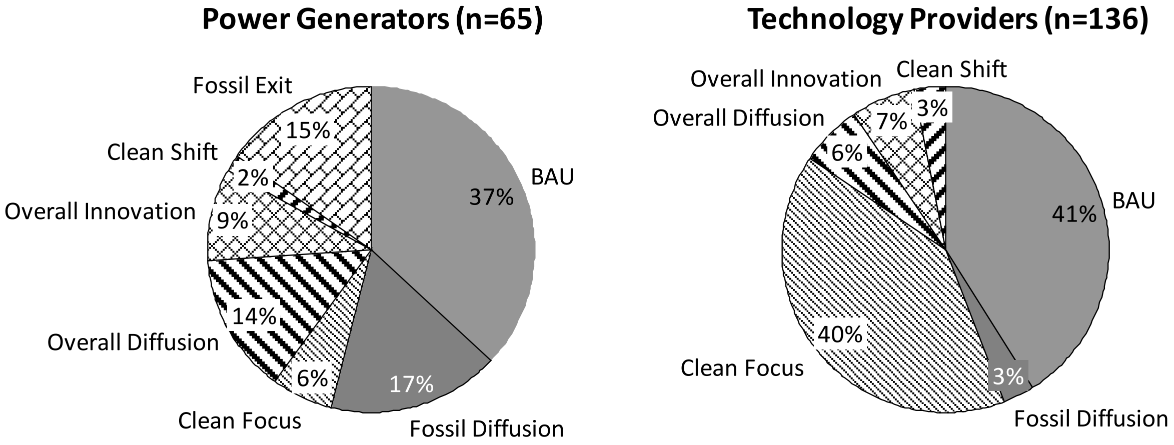

Figure 3: Distribution of the power generators (left) and technology providers (right) across the clusters

While the percentage of *BAU* is similar for both value chain steps, we find remarkable differences for the other firms. Power generators show very different behaviour changes, e.g., 17% increasing their fossil adoption activities and 15% reducing them. This picture is different for technology providers, where most of the non-*BAU* firms follow the *clean focus* pattern. From an evolutionary standpoint this is important as in the supplier dominated electricity sector it indicates that the firms relevant for creating novelty through R&D (technology providers) are contributing more to low-carbon TC than the regulated ones (power generators). Policy should therefore secure the growth and survival of these firms in order to assure TC at the sector-level. Table 3 summarizes all findings regarding the behavioural and characteristic heterogeneity from which we draw implications for policy makers (see next section).

Table 3: Summary of the findings

Cluster	Behavioural heterogeneity	Characteristic heterogeneity	
	Cluster's contribution to low-Carbon TC	Attributes	Policy perceptions
BAU	• None • Large inertia due to large size of cluster	• Medium values on all resources and capability variables	• Rather neutral perception of climate policy (LTT slightly positive) • Slightly positive perception of technology push policy • Rather positive perception of RET-pull policy
Fossil Diffusion	• Controversial via redirection towards fossil fuels	• Power generators • Large firms • Relatively fossil portfolios • Low technological capabilities	• Rather negative perception of climate policy (except for ETS 1&2) • Rather neutral perception of technology policy
Clean Focus	• Strong via acceleration and redirection • Strong via large size of cluster	• Technology providers • Medium size • Non-fossil portfolios • Moderate technological capabilities	• Throughout positive perception of climate policy • Throughout positive perception of technology policy (especially RET-pull)
Overall Diffusion	• Limited via acceleration	• Large firms • Diversified portfolios • Relatively low technological capabilities	• Rather neutral perception of climate policy • Neutral perception of technology push policy • Positive perception of RET-pull policy
Overall Innovation	• Medium via acceleration on both dimensions R&D and diffusion	• Large firms • Diversified portfolios • High technological capabilities	• Throughout slightly positive perception of climate policy • Throughout positive perception of technology policy
Clean Shift	• Strong via redirection • But limited due to small size of cluster	• Technology providers • Medium size • Non-fossil portfolios • High technological capabilities	• Throughout positive perception of climate policy • Slightly negative perception of technology push policy • Very positive perception of RET pull policy
Fossil Exit	• Medium via weakening of fossil technologies • But overall deceleration • Limited by relatively small size of cluster	• Power generators • Small size • Fossil portfolios • Low technological capabilities	• Negative perception of climate policy (especially LTT) • Slightly negative perception of technology push policy • Slightly positive perception of RET-pull policy

5. Policy implications

Our study provides first feedback on the decarbonisation of the power sector – one of the important objectives of European energy and climate policy – via TC. The results on the behaviour changes show that firms' contribution to low-carbon TC differ strongly. The fact that about 40% of the firms do not contribute to an acceleration and redirection of TC and another almost 8% contribute to a redirection to the fossil direction is important information for policy makers. This large inertia and the controversial behaviour changes cast doubt upon whether the current policy mix is able to trigger an acceleration and redirection of TC in the magnitude needed to meet the 450ppm target. Our results thus imply that the policy mix might need to become more effective.

Furthermore, the comparison of firms' attributes and policy perceptions provides novel information on the characteristic heterogeneity of differently behaving firms. While the policy mix might accomplish its purpose for some firms, other firms with potentially very specific characteristics need further incentives if large scale changes are to be achieved. We therefore hereafter discuss different groups of clusters along their contribution to the acceleration and redirection of TC, and derive recommendations on how the policy mix could be changed in order to raise each group's contribution to low-carbon TC.

The largest group of firms (*BAU*) does not significantly change its behaviour. Hence, they unveil the large inertia present in the sector. Interestingly, the firms in this cluster are not a very specific group but are instead highly heterogeneous regarding their attributes. One commonality appears to be the rather neutral perception of policies. In other words, climate and technology policy does not yet constitute a decisive element of their business environment (compare Rogge et al., 2011a). In order to become a decisive element, the stringency of policy needs to be increased. On the one hand, raising the EU's emission reduction goal from 20 to 30% and the ETS caps accordingly would be a potential measure, as is already being discussed. On the other hand, an expansion of stringent climate and low-carbon technology policy beyond the boundaries of the EU might increase the relevance of these policies for technology providers, which often innovate for global markets. To this end, the new targets and mechanisms agreed upon in Cancun (UNFCCC, 2011) need to be implemented in a stringent manner by national governments.

The fact that climate policy did not prevent power generators (*fossil diffusion*) with fossil fuel-heavy portfolios from predominantly investing in new fossil technology might seemingly point to a strong firm technology lock-in. However, the portfolios of these firms are not as fossil technology-heavy as those in the *fossil exit* cluster. An explanation might be the inverted incentives set by the allocation rules under the first phases of EU emission trading – this would explain why these firms perceive ETS 1&2 rather positively whereas they exhibit a negative perception of ETS 3 and LTT. While Ellerman and colleagues (2010) expect such effects ex-ante based on their economic models, first empirical studies (Schmidt et al., 2011) affirm these expectations. These effects are limited to the first two phases of the EU ETS in the power sector, as future allowances will mainly be allocated via auctioning. However, large over-allocations might still be present for industry sectors; the EU ETS 3 emission rights will also to a large extent be allocated for free via performance benchmarks (Cooper, 2010; Parker, 2010). The EU should apply certain stringency which at least prevents inverted effects and aim at harmonisation when defining these benchmarks (Clò, 2010).

Firms accelerating TC without clearly redirecting it (*overall innovation* and *overall diffusion*) are mainly larger firms with mixed portfolios. Their contribution to low-carbon TC depends strongly on the kind of investments made in fossil technologies. Should these investments lead to the significant decarbonisation of these technologies (e.g. via R&D in CCS) their contribution can be very important. Therefore, fossil push policies, i.e., R&D subsidies for fossil technologies, should not target incremental improvements that exacerbate the conditions preventing non-fossil fuel technologies from becoming competitive and thereby undermine ETS and RET pull policies. Only R&D that leads to substantial specific emission reductions should be supported. To this end, a stringent and consistent (Kern and Howlett, 2009) mix of climate and technology policies is needed, which all orient themselves along the same decarbonisation goals.

For another group of firms, the *fossil exit* cluster, climate and technology policy has served the purpose of decarbonisation only to a certain point. These power generators are heavily invested in fossil plants and directly targeted by climate policy. They perceive the new policy as a threat and took a first step by strongly reducing fossil investments. However, the policy mix does not (yet) prompt the second step of decarbonisation: investments in non-fossil technologies. Besides the potential influence of investment cycles, these results point to a certain lock-in of these firms in a fossil trajectory and/or the role of regulatory uncertainty in their hesitant behaviour (Engau and Hoffmann, 2011; Hoffmann et al., 2009). As technology policies are also not perceived as a big enough opportunity to trigger this second step, climate policy needs to be designed in a way which incentivises non-fossil investments. Price floors that signal a certain minimum stringency and thereby reduce regulatory uncertainty could be one measure (Hepburn et al., 2006; Neuhoff, 2011). A very recent analysis concluded that the potential pitfalls of such price floors can be avoided by smartly designed floor mechanisms (Wood and Jotzo, 2011). Another measure is integrating an incentive for investments in low-carbon technologies into climate policy: The EU's deliberations over embedding an "innovation/technology accelerator" to "reward companies [in industrial sectors] that invest in top performing technology and make significant emission reductions [...] by giving those installations additional free allowances on top of what could be expected from a normal implementation of the benchmark rules" (European Comission, 2010, p. 75) could also be applied to the power sector. However, technological change at the sector level can mean that certain firms dwindle in size or even disappear as market shares are taken over from firms which are more adapted to the new situation (Smith et al., 2005). Policy makers should include such scenarios and the respective lobbying pressure by the affected firms.

Finally, two clusters (*clean shift, clean focus*) have been identified which contribute to a redirection and acceleration of TC. Firms in these clusters perceive climate and technology policy as an opportunity. They are mainly providers of already aligned (non-fossil) technologies which gave up their small existing shares in fossil technology. Interestingly, the policy mix aiming at the decarbonisation of the sector seems to have only fully achieved its target for technology providers, though these companies are only indirectly affected by climate policy. The role of the suppliers in the power sector is underscored by these results.

Overall, the recommendations derived from the different groups' behaviour changes, attributes and policy perceptions show that the policy mix should be improved in several ways. However, designing a consistent and effective policy mix which is congruent to long-term targets is complicated in the political reality (Kern and Howlett, 2009; Meadowcroft, 2011). The EU generally has longer political time constants than those of the national governments in the member states and "avoids [...] to a large extent the politics of the party [...]. This results in the fact that apolitical EU civil servants rather than partisan legislators and their staffs are the primary drafters of legislation, and base their decisions primarily on technical and economic [and not political] grounds" (Schmidt, 2006, p. 105). For instance, pressures and lobbying from the aforementioned threatened firms can be more easily resisted by the EU than national governments. Hence, the EU should keep its guiding function for climate policy and enhance its role for coordinating technology and climate policies.

6. Conclusions

This paper delivers two main contributions. First, it presents novel empirical quantitative data on the role of the EU ETS and other important policies for technological change in the power sector. The results suggest that the current policy mix might not be effective enough to trigger the effects needed to achieve the 450 ppm target. Second, our study complements existing empirical and theoretical studies which analyse the effectiveness of the policy mix in the power sector. Apart from the innovation system literature (e.g., Rogge and Hoffmann, 2010), the role of differences between relevant affected actors has often been overlooked in the academic debate thus far. Most studies are predominantly concerned with the effects of the different instruments and/or their interactions (for an overview see Fischer and Preonas, 2010). However, these studies mostly exclude the fact that these instruments' effects and their interactions can differ for heterogeneous firms. Our study places special emphasis on this dimension, which is very relevant for explaining technological change. This allows us to derive indicative recommendations on how to adjust the policy mix in order to induce contributions from all heterogeneous firms in the power sector.

Our study has several limitations which call for future research however. Further attributes of firms in the power sector might be included in future analyses, such as firm ownership and the national or international market orientation of a firm, both of which touch on a firm's innovation decisions. Above that, other important policies in the power sector such as energy price regulations have been omitted. It would also be of great interest to track the firms' organisational change as it is a condition 'sine qua non' for changing behaviour (Nelson, 1991). Finally, our analysis is based on relative numbers regarding the innovation activity changes. Firms with different sizes are thus counted equally, although their contribution to technological change can diverge widely. The results of our study should therefore be compared to those of studies based on macro data, which shows trends in R&D and diffusion for the entire sector, as soon as this data is available.

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ANNEX

Table A1: Country of origin of respondents[9]

Group	France	Germany	Italy	Poland	Slovakia	Spain	UK
Power generators (65)	2%	49%	14%	15%	5%	15%	-
Technology providers (136)	5%	38%	19%	8%	4%	21%	5%

Table A2: Descriptive statistics of the sample

		min	max	mean	std.dev.
innovation pattern change	non-fossil R&D	-2.00	2.00	.53	.79
	fossil R&D	-2.00	2.00	.10	.54
	non-fossil diffusion	-2.00	2.00	.83	.91
	fossil diffusion	-2.00	2.00	.22	.77
resources & capabilities	vc position*	1.00	2.00	1.68	.47
	Size (turnover)	.00	6.00	2.80	1.51
	share fossil (in %)	.00	100.00	35.44	42.45
	Tech capabilities	-.45	6.06	.00	.91
policy perception	ETS 1 & 2	-2.00	2.00	.19	.81
	ETS 3	-2.00	2.00	.11	.99
	LTT	-2.00	2.00	.35	1.17
	Tech.-push policy	-2.00	2.00	.38	.83
	RET-pull policy	-2.00	2.00	.98	1.01

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[9] The strong bias towards Germany is to a large extent based on the very high number of (small) utilities in that country compared to the other countries. A similar trend can be observed in the technology provider sample. While France and the UK are clearly underrepresented in our sample, the other numbers roughly represent the entire population of electricity generation technology providers in the population.

Annex II

Curriculum Vitae

Curriculum Vitae

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Education

05/08 - present	ETH Zurich, Switzerland	*Doctorate studies* at the Department for Management, Technology and Economics
10/02 - 04/08	TU München	*Studies in Electrical Engineering (BSc. & Dipl. Ing.)* specialized in the fields of *Electrical Power Engineering and Energy Economics* Grade Dipl: A (1.5), Grade BSc: A- (1.8); scale: 1 (=best) to 5
02/06 - 06/06	MMU Malaysia	*Exchange student at MM University Malaysia* Studies in mechanical engineering
10/00 - 09/02	Siemens AG, Munich	*Commercial apprenticeship (Stammhauslehre) at Siemens AG, Munich* German Chamber of Industry & Commerce – Exam: 95% Siemens internal exam (FAP): 1.4; scale: 1 (= best) to 6
09/91 - 06/00	High School	*Gymnasium Geretsried* high school diploma (Abitur): A (1.2); scale: 1 (= best) to 6 intensive courses: Latin, Geography
09/87 - 08/91	Primary School	*Grundschule Eurasburg*

Academic Activities

09/08 - Present	***Teaching:*** Modules in 4 lectures on climate change, corporate environmental strategies, carbon markets and managerial economics
09/11 - 09/11	***Visiting fellow*** at Utrecht University (Prof. Marko Hekkert)
05/08 - 03/11	***Teaching***: Supervision of 6 students in the Master of Science and 2 students in the Master of Advanced Studies programmes
01/11 - 02/11	***Research exchange***: Visitor to the Tokyo Institute of Technology (Prof. Norichika Kanie) under the "Exchange program for excellent young ETH Zurich researchers"; Setup of future collaboration between Tokyo Tech and SusTec
05/08 - 12/10	***Management of research project*** "Corporate Climate Innovation Strategies in response to International Market-based Climate Policies" funded by Volkswagenstiftung (400,000€ for 3.5 years); reporting, fund management, survey of over 1500 firms in seven EU countries, supervision of 7 student assistants

Selected Professional Experience

05/07 - 08/07 and 07/04 - 02/05	TU München, Munich, Germany	*Student assistant at the Institute for Energy Management & Technology (Prof. Wagner)* Excellence Cluster: Energy Situation Bavaria 2030; assembly of experimental rig: CHP cycle; analyzes of technological branches (Power suppliers, alternative drive vehicles)
01/07 - 03/07	United Nations, New York, USA	*Intern with the UN Department of Economic and Social Affairs, Energy Statistics Section* Energy Country Profiles, Assessment of potentials for renewable energies; support for 60th UN Statistical Commission Assembly
07/06 - 09/06	Siemens Malaysia, Kuala Lumpur	*Intern with Siemens Power Generation Asia Pacific* Sales for Performance and Efficiency Improving Control System, Responsibility for two customers; Support for technical sales, representation towards customers
03/05 - 01/06	Siemens AG CT ES & TU München, Munich, Germany	*Working Student and Bachelors Thesis with Corporate Environmental Affairs and Technical Safety Department* Consulting Project for the improvement of the energy efficiency at four plants of Siemens VDO Automotive AG

Languages

German (mother tongue)
English (fluent)
Spanish (good knowledge)
Latin (reading)

Computer Skills

MS Office Package, Virtual Basic, C, SPSS, STATA

Scholarships / Prices

‘03-08: Scholarship by the German National Academic Foundation (Studienstiftung des Deutschen Volkes)

‘06: Scholarship by the SUTOR- Foundation for studies in Malaysia (living costs)

’06: Scholarship by the TU München, LAOTSE- Exchange Program for studies in Malaysia (tuition fees)

’00: Winner of the promotional award at the German Federal Environmental Competition “Bundesumweltwettbewerb”, awarded by the Minister of State for Education & Research

Publications

Peters M., Schmidt T.S., Wiederkehr D., Schneider M. (2011): "Shedding light on solar technologies – a techno-economic assessment and its policy implications", Energy Policy (in press)

Rogger C., Beaurain F., Schmidt T.S. (2011): "Composting Projects under the Clean Development Mechanism: Sustainable Contribution to Mitigate Climate Change" Waste Management 31 (2011) 138–146

Schneider M., Schmidt T.S., Hoffmann V.H. (2010): "Performance of Renewable Energy Technologies under the CDM", Climate Policy 10 (2010) 17–37

Rogge K.S., Schmidt T.S., Schneider M. (2011): "Relative Importance of different Climate Policy Elements for Corporate Climate Innovation Activities: Findings for the Power Sector" in "Carbon Pricing for Low-Carbon Investment" by Climate Policy Initiative (CPI)

Review activities

Journal referee for *Climate Policy* and *Waste Management.*