



Doctoral Thesis

Creating Markets for Energy Innovations Case Studies on Policy Design and Impact

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Creating Markets for Energy Innovations

Case Studies on Policy Design and Impact

A thesis submitted to attain the degree of
DOCTOR OF SCIENCES of ETH ZURICH
(Dr. sc. ETH Zurich)

presented by
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“Geez, Lisa, looks like tomorrow I’ll be shoveling 10 feet of global warming.”

Homer Simpson

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What a journey!

Abstract

The urgency of the world's environmental challenges has led governments around the globe to rethink the role of government in the innovation process. In addition to direct public spending on energy technology research, development and demonstration, many countries now subsidize the large-scale deployment of innovative energy technologies through so-called 'deployment policies'. Examples include feed-in tariffs for renewable electricity, mandates for the blending of biofuels and investment subsidies for electric vehicles. Deployment policies can be expensive ways to mitigate the current environmental footprint of the energy system, but proponents justify them as 'learning investments' which will pay off in the long term as they stimulate innovation, bring down cost and enhance the performance of clean energy technologies for future generations. The debate on the validity of this claim is controversial and politicized, in part because the discussion often lumps together very different technologies and paints a simplified picture of the complex process of system transformation. This thesis presents six essays to advance this debate, three on the nature of the innovation process in different energy technologies and three on the design and governance of deployment policy instruments. Collectively, these essays make three distinct contributions.

First, this thesis introduces a novel methodology to study the evolution of technology. A combination of patent content analysis and citation-network analysis, the method developed in this thesis allows to quantitatively study the focus of research activity in a sector over time and across geographies. In the future, this methodology will allow to study a number of under-researched phenomena in the evolution of technology, including (i) the relationship between the focus of research activity and competitive advantage; (ii) the division of labor in research and development between countries and regions in global value chains; (iii) the impact of public policy on shifts in the focus of research activities.

Second, this thesis introduces the explicit consideration of differences in the innovation process between energy technologies into the analysis of deployment policies. It shows that the model of the technology life-cycle that is implicitly assumed in much of the current debate on deployment policies applies to mass-produced energy technologies, but does not adequately describe innovation in complex infrastructure technologies in the energy sector. This is important because different models of the life-cycle imply different roles for deployment – and thus deployment policies – in the evolution of technology. It means that the conceptual underpinnings of the debate on deployment policies do not apply to a significant share of the energy technology space, and calls for the explicit consideration of

technological characteristics in decisions on deployment policy support for energy technologies, in particular the size, duration and geographical scope of support. It also allows us to reconcile conflicting evidence on the impact of deployment policies in the literature. These findings are based on three case studies in the first three essays of the thesis: (1) an analysis of the focus of inventive activity over time in wind turbine technology in 1973-2009, using a novel methodology that integrates expert assessment of patent data with patent-citation network analysis; (2) a comparison of technology life-cycles in wind turbine technology and solar PV technology in 1970-2009, using the same methodology; and (3) a techno-economic model of the impact of local and global learning on the cost of renewable energy deployment in Thailand in 2013-2021.

Third, this thesis' results emphasize the need to consider the complex political dynamics of socio-technical transformations in the debate on energy innovation policies in general and deployment policies in particular. In most technology policy analyses, policy decisions are seen as essentially exogenous to the technological change the intervention aims to induce. In practice, this means that the possibility of changes to public policy in response to induced technological change is not part of the analysis, nor is the ability of affected actors to foresee or respond to such changes. Essay 4 demonstrates that this may not adequately reflect political reality. The essay presents a qualitative analysis of the evolution of Germany's public policy support for solar power in 2000-2012. The essay demonstrates that deployment policy instruments can become at least in part endogenous to the transformation they were designed to induce, because they trigger unforeseen changes in the socio-technical system, and develops a model to account for these dynamics. The findings have two important implications. First, because investors in innovative energy technologies are aware of the possibility of policy changes, the effect of deployment policies on innovation will depend, at least in part, on the political system and its ability to learn and respond. Second, the ability of a policy to induce desired technological outcomes will depend as much on the design of the policy itself as on the state of the socio-technical system. Policy designs and lessons learned can therefore not always be transferred between jurisdictions – e.g., the fact that Germany may no longer need costly feed-in tariffs to attract investment in photovoltaics does not mean this policy is not the most cost-efficient option to attract investment in other jurisdictions. The last two essays explore these two implications in more detail. Essay 5 reviews and analyzes the proposals for internationally supported feed-in tariffs for renewable energy in developing countries, and discusses how to minimize the risk premium demanded by investors due to the policy risk induced by the prospect of unforeseen cost developments.

Essay 6 explores the implications of the German experience with deployment policies for solar power in the context of the newly introduced feed-in tariff for renewable electricity in Japan.

Zusammenfassung

In Anbetracht dringlicher globaler Umweltprobleme, wie etwa des Klimawandels und der urbanen Luftverschmutzung, wird die Rolle des Staates der Entwicklung innovativer Technologien seit einiger Zeit neu diskutiert. Neben der traditionellen öffentlichen Förderung von Forschung, Entwicklung und Demonstrationsanlagen subventionieren viele Regierungen neuerdings auch den großtechnischen Einsatz innovativer Energietechnologien durch sogenannte „Nachfrageinstrumente“, wie zum Beispiel Einspeisetarife für Strom aus erneuerbaren Energien, Mandate für die Beimischung von Biokraftstoffen oder Investitionszuschüsse für Elektroautos. Geht es nur um die Reduktion des momentanen ökologischen Fußabdrucks des Energiesystems, sind diese Nachfrageinstrumente oft vergleichsweise kostenintensiv. Befürworter argumentieren jedoch, dass es sich bei Nachfrageinstrumenten um "Lerninvestitionen" handelt, welche sich auf lange Sicht durch induzierte Innovationen, Kostenreduktionen und Effizienzsteigerungen auszahlen werden.

Die wissenschaftliche und öffentliche Debatte über den Innovationseffekt von Nachfrageinstrumenten ist kontrovers und politisiert. Dies liegt unter anderem daran, dass unterschiedliche Technologien in der Debatte nicht ausreichend differenziert werden. Auch wird oft ein sehr vereinfachtes Bild der komplexen, systemischen Transformationsprozesse und ihrer Determinanten gezeichnet. Die vorliegende Dissertation umfasst sechs Artikel, die darauf abzielen, bezüglich dieser zwei Aspekte mehr Substanz in die Debatte zu bringen. Die ersten drei Aufsätze befassen sich demnach mit technologiespezifischen Faktoren im Innovationsprozess in unterschiedlichen Energietechnologien. Die nächsten drei Aufsätze befassen sich mit der Gestaltung und zeitlichen Dynamik von Nachfrageinstrumenten im Kontext von komplexen, systemischen Transformationen und der daraus resultierenden Unsicherheit. Im Folgenden sollen die drei wichtigsten Beiträge dieser Arbeit herausgearbeitet werden.

Erstens, diese Dissertation entwickelt eine neue Methodik, mit der die Evolution von Technologien untersucht werden kann. Die Methodik integriert Ansätze aus der Patentanalyse und der Netzwerkanalyse und ermöglicht es, die Entwicklung eines komplexen technischen Systems über Zeit und in ihrer räumlichen Ausprägung quantitativ zu analysieren und graphisch darzustellen. Diese Methodik wird es in der Zukunft erlauben, eine Reihe von bisher kaum untersuchten Phänomenen genauer zu untersuchen, wie etwa (i) die Beziehung zwischen dem Fokus industrieller Forschung und Wettbewerbsvorteilen; (ii) die räumliche und betriebliche Arbeitsteilung in der Entwicklung

komplexer technischer Systeme; und (iii) die Auswirkung von regulatorischen Interventionen und öffentlicher Förderung auf den technologischen Fokus der industriellen Forschung.

Zweitens, diese Dissertation stellt dar, wie relevante Charakteristika von Energietechnologien in die Gestaltung und Evaluation von Nachfrageinstrumenten mit einbezogen werden können. In den ersten drei Artikeln dieser Arbeit wird empirisch aufgezeigt, dass sich Innovationsprozesse in verschiedenen Energietechnologien deutlich hinsichtlich ihrer zeitlichen und räumlichen Muster unterscheiden. Die so herausgearbeiteten Technologiecharakteristika ermöglichen es, widersprüchliche Aussagen über die Innovationseffekte von Nachfrageinstrumenten in der wissenschaftlichen Literatur in Einklang zu bringen. Darüber hinaus ergeben sich aus einer Differenzierung von Technologien nach den herausgearbeiteten Charakteristika wichtige technologiespezifische Implikationen für die räumliche und strategische Ausgestaltung von Nachfrageinstrumenten. Die Ergebnisse beruhen auf einer Analyse des Fokus der Forschungstätigkeit in der Windturbinentechnologie im Zeitraum 1973-2009 (Aufsatz 1); einem Vergleich der Technologielebenszyklen in der Windturbinentechnologie und der Photovoltaik im Zeitraum 1970-2009 (Aufsatz 2); und einer Modellierung der Auswirkung von lokalen und globalen Lerneffekten auf die Kosten von erneuerbaren Energien in Thailand im Zeitraum 2013-2021 (Aufsatz 3).

Drittens, diese Dissertation arbeitet heraus, wie die komplexe Dynamik von systemischen Transformationsprozessen und die daraus resultierende Unsicherheit in der Gestaltung von Nachfrageinstrumenten berücksichtigt werden können. In der Innovationspolitikforschung wird die Gestaltung und der Umfang von öffentlichen Technologiesubventionen üblicherweise als exogen angenommen. Aufsatz 4 zeigt jedoch, mithilfe einer qualitativen Analyse der Entwicklung der politischen Förderung für die Photovoltaik im Zeitraum 2000-2012 in Deutschland, dass es eine starke „Rückkopplung“ zwischen Innovationspolitik und technologischem Wandel gibt. Technologische Veränderungen in der Photovoltaikindustrie in Deutschland, welche von staatlichen Subventionen ermöglicht wurden, führten wiederholt zu politischem Druck die Subventionspolitik anzupassen und zu reformieren. Das beschriebene, komplexe Zusammenspiel zwischen Innovationspolitik und technischem Wandel hat zwei Implikationen. Zum einen können Förderinstrumente nicht ohne weiteres zwischen Ländern übertragen werden, da die momentan „optimale“ Förderpolitik vom technologischen Stand der geförderten lokalen Industrie abhängt. Zum anderen hat das Zusammenspiel Auswirkungen auf die Fähigkeit von politischen Förderinstrumenten, langfristige Investitionen anzuziehen: die Erwartungen von Investoren bezüglich der politischen Nachhaltigkeit eines Subventionsregimes beeinflussen direkt die verlangte Risikoprämie in den

Kapitalkosten, und damit die Attraktivität von risikoreichen und langfristigen Investitionen. Die letzten beiden Essays vertiefen die Diskussion der Implikationen der Aufsätze 1-4 für die Gestaltung von Nachfrageinstrumenten. Aufsatz 5 diskutiert und analysiert unterschiedliche Vorschläge für finanziell unterstützte Einspeisetarife für erneuerbare Energien in Entwicklungsländern. Der Aufsatz diskutiert wie diese Einspeisetarife gestaltet werden können, so dass die Risikoprämie, welche von Investoren verlangt wird um das Risiko nachträglicher Politikänderungen abzusichern, minimiert werden kann. Aufsatz 6 diskutiert die internationale Übertragbarkeit von politischen Instrumenten, insbesondere wie die deutschen Erfahrungen mit Einspeisevergütungen für Erneuerbare Energien auf Japans neue Förderpolitik übertragen werden können.

Synopsis

1. Introduction

1.1. Mitigating Climate Change: A Mammoth Technological Challenge

At the Earth Summit in Rio de Janeiro in 1992, the world's leaders formalized their intention to “stabilize greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” as part of the United Nations Framework Convention on Climate Change (UNFCCC, 1992). At the 2009 UNFCCC conference in Copenhagen, “dangerous anthropogenic interference” was clarified when leaders agreed on the objective to keep global warming within 2°C (UNFCCC, 2009). But total anthropogenic GHGs have continued to increase since the first negotiation of the UNFCCC, as well as following Copenhagen in 2009, despite a growing number of national and international climate change mitigation policies. In fact, GHG emission growth *accelerated* to 2.2% in the period 2000-2010 compared with 1.3% in 1970-2000. Roughly three quarters of this increase come from carbon dioxide (CO₂) emissions from fossil fuel combustion and industrial processes, two sources which together account for about 65% of global GHG emissions (IPCC, 2014).

The time window to reduce GHG emissions is rapidly closing (Sanford et al., 2014). The Intergovernmental Panel on Climate Change (IPCC) estimates that total cumulative emissions must not exceed one trillion tons of carbon equivalents (1,000 Gt C) in order to stay, at 66% probability, within 2°C of global warming (IPCC, 2013).¹ This is equal to about 30 years at current emissions levels – not much more than the 22 years the world has already spent trying to negotiate a comprehensive international climate agreement (see Figure 1). The United Nations Environment Program (UNEP) expects the world to significantly ‘overshoot’ this budget (UNEP, 2014).²

Recent international political developments seem to corroborate UNEP's expectation. Even when taking into account the pledges made in the recent joint announcement made by China and the

¹ Sustained GHG emissions at current levels are not compatible with scenarios that keep global warming within 2°C. Because a significant share of emitted GHGs remain in the atmosphere for millennia, it is useful to think in budgets for cumulative GHG emissions.

² Under business as usual assumptions, GHG emissions are estimated to increase to 87 Gt CO₂eq in 2050, compared to about 54 Gt in 2012 (UNEP, 2014).

United States, China's GHG emissions, which now stand at 28% of the world's total (Friedlingstein et al., 2014), will continue to rise until 2030 (The White House, 2014). Reductions from the US and Europe equivalent to China's projected emissions growth are unlikely in that timeframe (UNFCCC, 2014; Zhang et al., 2014). Given this trajectory, the global economy will have to become *net carbon negative* before the end of the century (as shown in Figure 1) in order to stay within 2°C of global warming, e.g., through the large scale deployment of carbon-negative bioenergy (Tilman et al., 2006).

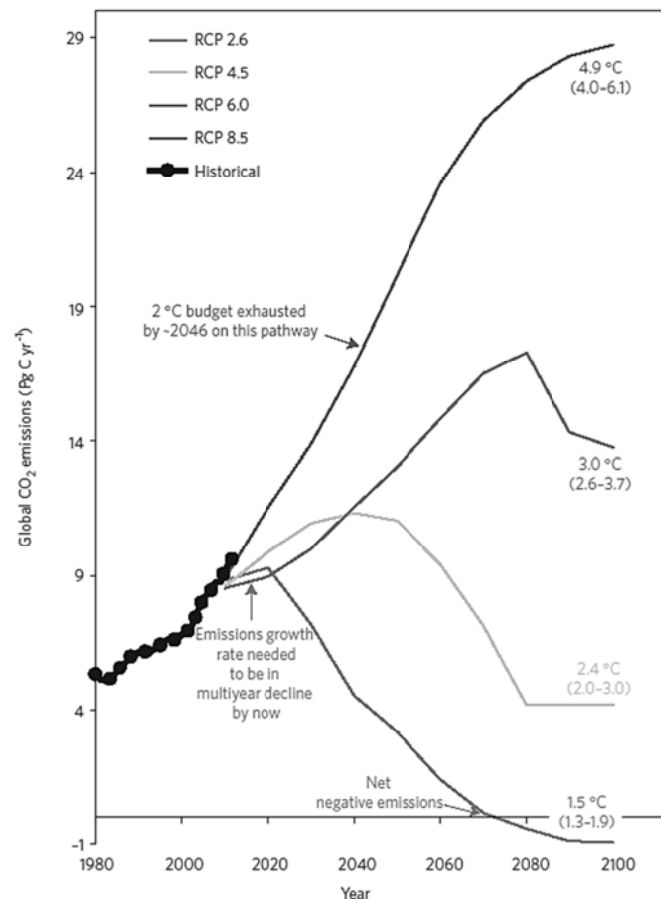


Figure 1: Observed and projected trends in global CO₂ emissions under four IPCC scenarios (Sanford et al., 2014). Trends include both fossil fuel and industrial emissions, but not land use change emissions (e.g., deforestation and wetland loss). Numbers on the right-hand side represent the median values of global mean surface temperature projections above pre-industrial levels in 2100 and the 66% probability range of the ensemble projections for each scenario. The 2046 budget number is determined from the allowable carbon emissions budget of 1,000 Pg C consistent with a >66% likelihood of limiting warming to less than 2°C.

At the same time, there is pressure to increase emissions even further. Globally over 1.2 billion people live in extreme poverty (The World Bank, 2013). 1.3 billion people – 18% of the world's population – are without access to electricity, and 2.7 billion people rely on the traditional use of biomass for cooking, which causes harmful indoor air pollution (IEA, 2014a). In the absence of a significant reduction in the carbon intensity of the world economy, understood here as tCO_{2eq} per \$ of economic

output, sustaining economic growth and providing access to energy services will lead to a strong increase in emissions. China's economic transformation over the last three decades lifted 600 million people out of poverty and provided access to electricity to almost 100% of the country. But it also had an enormous climate footprint: China's GHG emissions per capita are now 6% higher than those of the European Union, even though income per capita is only about one-fifth (Friedlingstein et al., 2014). Facilitating the same rates of growth in income and energy access in South America, South Asia and Africa while staying within the one trillion ton budget will require nothing short of a technological revolution (Galiana and Green, 2009).

1.2. In Search for a Technological Revolution in the Energy Sector

Much of the technological revolution required to mitigate climate change will have to take place in the electricity, heat and transport sectors (collectively referred to in this thesis as the *energy sector*). In 2010, the energy sector was responsible for 65% of anthropogenic CO₂ emissions (IEA, 2014b). As can be seen in Figure 2, which shows a sectoral split of CO₂ emissions over time, most of the increase since the 1970s came from one sector: electricity generation. In fact, the recent acceleration in the 2000–2010 decade described above can be attributed almost entirely to an increase in coal use for electricity production, in particular in China (IPCC, 2014). Overall, global total primary energy supply more than doubled between 1971 and 2012 (IEA, 2014b).

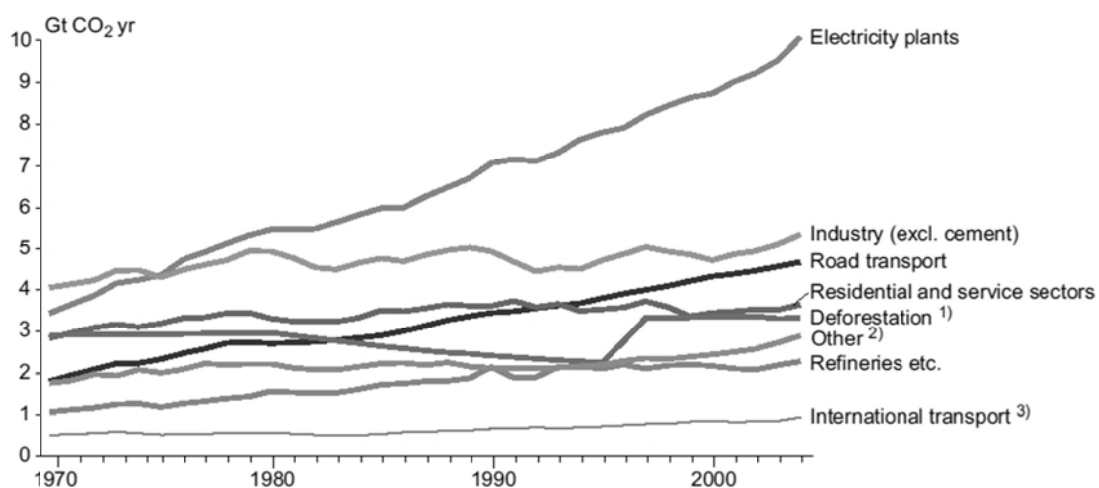


Figure 2: Sources of global CO₂ emissions, 1970–2004 (only direct emissions by sector) (IPCC, 2007). ¹Including fuelwood. ²Other domestic surface transport, non-energetic use of fuels, cement production and venting/flaring of gas from oil production. ³Including aviation and marine transport.

Scenarios by the IPCC suggest that the electricity sector will play a key role in mitigating climate change, for three reasons. *First*, under business-as-usual assumptions the emissions from the electricity

sector will rise more rapidly than from any other sector of the economy. *Second*, in scenarios consistent with the 2°C target, decarbonization happens more rapidly in electricity generation than in any other sector, and the sector becomes net negative by mid-century. *Third*, low carbon electricity can reduce the cost of emission reductions in other parts of the energy sector, e.g., in the form of electric heating, electric vehicles, and increasing use of electricity in industry (IPCC, 2014).

Options exist to provide energy at low, zero or even net negative GHG emissions. As shown in Figure 3, the combined global technical potential to provide electricity, heat and transport from renewable energy sources exceeds current demand by several orders of magnitude. However, there are many social and political barriers that keep these technologies from being deployed, which mean that the development of better and cheaper technologies will not solve the climate challenge (Unruh, 2000). Having that said, it is clear that clean energy technologies will need to improve in terms of cost and performance in order to be adopted across the economy (Edenhofer et al., 2012).

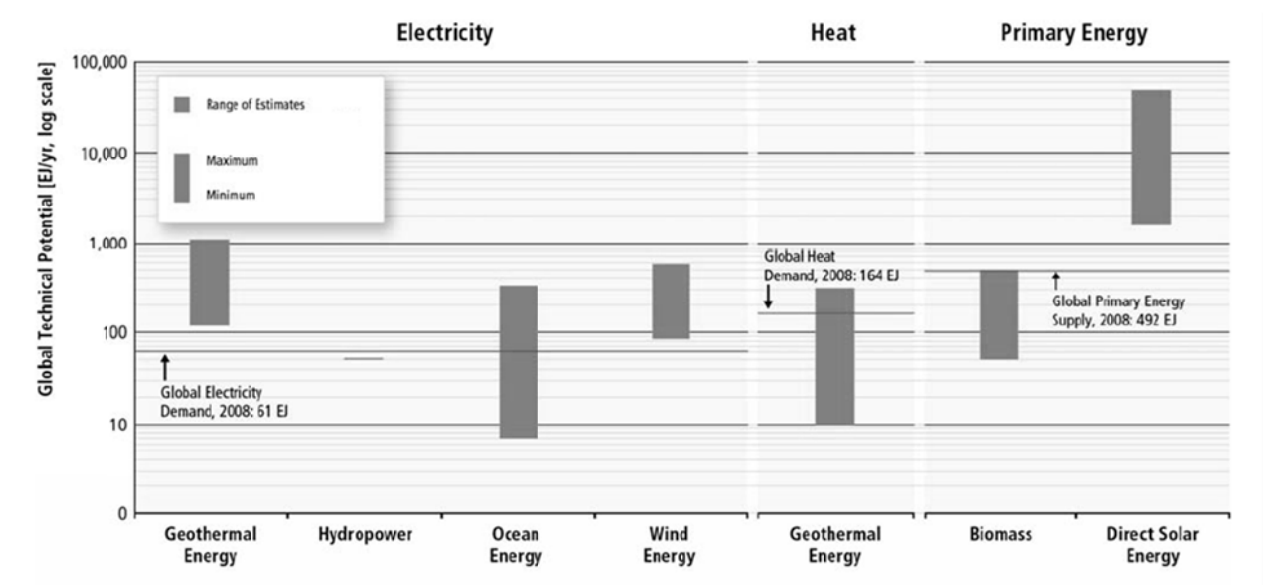


Figure 3: Ranges of global technical potentials of RE sources in studies reviewed by the IPCC (Edenhofer et al., 2012). Biomass and solar are shown as primary energy due to their multiple uses. Note that the y-axis values are presented on logarithmic scale due to the wide range of assessed data.

Industrialized countries have sought to reduce dependency on fossil fuels in the energy sector since the oil crises in the 1970s. The deployment of non-fossil fuels has increased in absolute terms, largely nuclear and hydropower, but has not managed to outpace increasing demands for energy related to worldwide economic growth and development. In 2012, fossil fuels still accounted for 82% of the world primary energy supply, a share that has decreased by only 4% since 1972 (IEA, 2014b).

In the last decade, the deployment of clean energy technologies has accelerated, especially in the electricity sector. The International Energy Agency (IEA) estimates that investment in renewables-based power plants accounted for 58% of global power generation investment between 2000 and 2013 (IEA, 2014a). Most of this now went into wind and solar photovoltaic (PV) power, which accounted for 70% of investment in OECD countries since 2000. Overall investment in clean energy technology increased five-fold over 2000-2013, reaching a peak of \$290 billion³ in 2011 (\$2.3 trillion in total) (IEA, 2014a).⁴

Notably, a large share of investment into clean energy technologies is being made in developing countries. A group of 55 countries surveyed by Bloomberg New Energy Finance (BNEF) had 666GW of renewable electricity capacity installed in 2013, compared to a total of 806GW in OECD countries. On average, renewables (including large hydro) represented a larger percentage of total capacity in these nations than they do in the OECD (BNEF, 2014).

Despite these efforts, clean energy is not replacing fossil fuels at the rates necessary to mitigate dangerous climate change impacts (Loftus et al., 2014). Technological change must progress much more rapidly in the immediate future than it has in the last four decades. This will require substantial public policy support for innovations in energy (Trancik, 2014).

2. Policy Relevance

2.1. A Growing Role for Government in Energy Innovation

There are two widely accepted rationales for public policy support of energy innovation (Jaffe et al., 2005; Gallagher et al., 2012). First, social benefits exceed private benefits when utilities or other users *adopt clean energy technologies* because of distortions in the markets for energy goods and services. These market failures justify government investments to advance the public interest (e.g., Gillingham and Sweeney, 2010). Most obviously, the social cost of pollution from fossil fuels is rarely reflected in the price of electricity, heat or transport. Even in jurisdictions that put a price on pollution, e.g., through taxes or emissions trading schemes, the price signal tends to be much lower than the social cost of

³ All dollar values in this thesis are in USD.

⁴ 90% of this went into power generation technologies, the rest into biofuel refineries.

pollution and too uncertain to stimulate innovations (e.g., Schmidt et al., 2012; Taylor, 2012). But there are also more subtle ways in which markets for energy favor the technological status quo. Fossil fuel technologies are deeply embedded in formal and informal institutions in the energy sector – e.g., in standards, regulations and market power – as a result of a century-long co-evolution (Walker, 2000). The same issue is found within the physical infrastructure, where technological complementarities, economies of scale and network effects favor technologies that are widely in use over emerging alternatives (Unruh, 2000).

The second widely accepted rationale is that the social benefits from the *development of new clean energy technologies* exceed the private benefits of technology providers. Therefore, even if price signals in the markets for energy goods and services would be corrected for all market failures described above, firms would still underinvest in clean energy innovation (Gallagher et al., 2011). This is because, on one hand, investments in innovation are in general very risky, and options to insure this risk are limited. Furthermore, social benefits of innovation often accrue far into the future and outlive the time horizon of private investors. Lastly, knowledge generated in the innovation process can ‘spill over’ to other firms. Such knowledge spillovers can represent significant barriers, especially when investments are large and very visible, e.g., in the case of first-of-a-kind commercial-scale plants (Weyant, 2011; Nemet et al., 2014).

The world’s inability to respond to climate change has made these market failures particularly salient in the public discourse. Various stakeholders, therefore, urge governments to enlarge the size and scope of public policy support for innovation in energy, calling for public investments to accelerate different stages of the energy innovation process – in R&D, demonstration, niche markets or large-scale deployment of clean technologies (e.g., AEIC, 2010; Anadon et al., 2011; Gallagher, 2009; PCAST, 1997; Shellenberger et al., 2010). In response, governments around the globe are rethinking the role of the state in energy innovation (Mowery et al., 2010; Henderson and Newell, 2011; Mazzucato, 2011; Foray et al., 2012).

Whether public resources are better spent on research, development and demonstration (RD&D) or later stages of the energy innovation process is controversially debated in the academic community. Some argue that the “non-incremental innovation” that we need is “more responsive” to research funding and much less to investments in later stages of the innovation process (Nemet, 2009, p. 708). Others counter that climate change and resource depletion “cannot be simply researched away” (Yang and Oppenheimer, 2007, p. 203) and that “the achievement of a technical goal in the field of

alternative-energy technologies is only the beginning of a long process of learning, incremental improvement, and monitoring of the performance of these technologies in a wide array of complex operating environments”, which must be supported through public investments in technology deployment (Mowery et al., 2010, p. 1201).

2.2. Shifting Priorities: From RD&D to Market Creation

While the academic debate on the relative merits of investments in energy RD&D and deployment is still ongoing,⁵ government actions lean heavily toward the latter.

Governments are spending a non-trivial amount of public resources on RD&D for energy technologies – in 2011, the world total was in the range of \$20-30 bn (Kempener et al., 2012; IEA, 2014c). However, despite a series of calls for a significant increase in energy RD&D (e.g., IEA, 2013; Nemet and Kammen, 2007; PCAST, 1997), absolute spending has increased only slightly over the last decade (see Figure 4). In terms of its share of global GDP, it has even declined. Compared to other public spending priorities, energy RD&D spending looks particularly dismal: defense alone consumes about 30% of the public RD&D budget in IEA-member countries, almost ten times as much as energy. The IEA recommends at least three times the current spending to stay within 2°C; the spending gap for clean vehicles and carbon capture & storage alone is estimated to be at least USD 30bn (IEA, 2013).

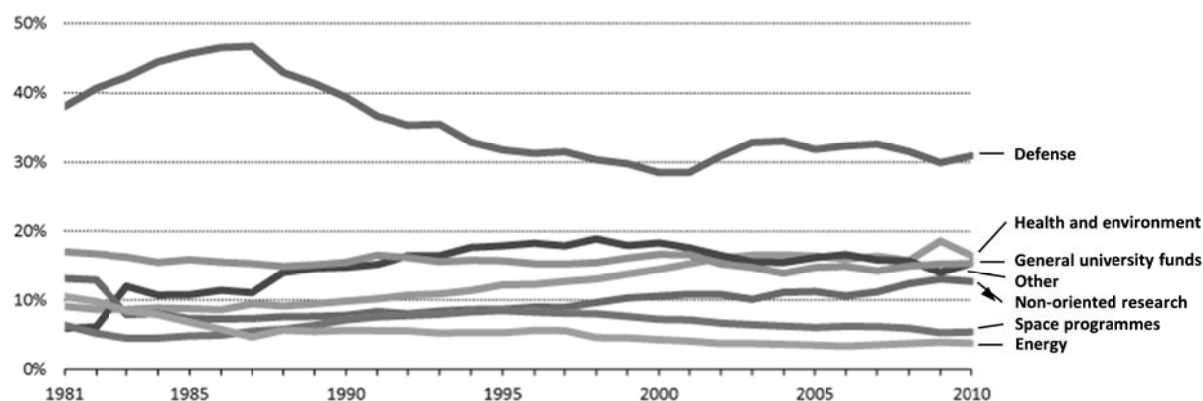


Figure 4: Public spending on energy research, development and demonstration (RD&D) in relation to other research areas, as a share of total public RD&D spending (IEA, 2013).

⁵ See, e.g., the discussion section on technology policy and global warming in Research Policy 39 (8).

At the same time, governments around the globe are rapidly increasing their subsidies to create markets for the large-scale deployment of innovative energy technologies. In many cases, spending on these ‘deployment policies’ (Hoppmann et al., 2013) or ‘market formation policies’ (Gallagher, 2014), which includes subsidized electricity tariffs for renewable electricity, blending mandates for biofuels, and tax credits, now exceed RD&D support by orders of magnitude. Figure 5 shows projections by the IEA for subsidies supporting the deployment of renewable energy technologies. In 2013, subsidies to renewables were \$121bn, 15% higher than in 2012 and almost three times as much as in 2007.

These numbers mean that spending on deployment policies for renewable energy was four to six times as much as RD&D subsidies for all energy technologies combined (IEA, 2014a). This ratio is even more skewed in certain technological areas and jurisdictions. For example, EU member countries spent 35-41 times more on deployment for solar PV and wind power than on R&D (Laleman and Albrecht, 2014); in Germany, the ratio was 100:1 for PV and 50:1 for wind power in 2011 (E-FI, 2014, p. 63). In the US, China and Japan, deployment policy support for wind and PV also outweighs R&D funding for renewable energy by at least one order of magnitude (e.g., by factor 20 in the case of wind power in the US) (GAO, 2013). This trend is likely to continue, as seen in Figure 5: the IEA predicts that between 2007 and 2040, a total of \$5.1 trillion will be spent on deployment policies.

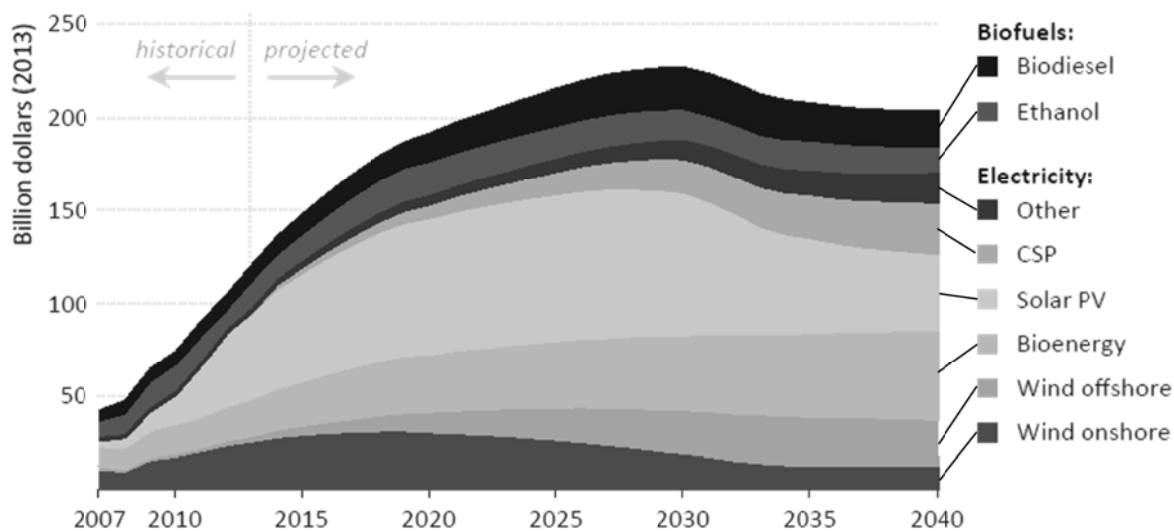


Figure 5: Historic and projected spending on deployment policies for renewable energy. For power, spending is calculated as the difference between the cost of electricity and the wholesale price in each region, multiplied by the amount of generation for each renewable energy technology. For biofuels, spending is calculated by multiplying the consumption by the difference between their production cost and the regional reference price of the comparable oil-based product in each region (IEA, 2014a).

Unlike traditional climate policies, these deployment policies are not only intended to stimulate the adoption of existing low-carbon technologies, but have the explicit objective to reduce costs and improve performance of clean technologies in the future. For example, the German feed-in tariff for solar power (a form of subsidized electricity tariff), at about \$10bn per year the most expensive deployment policy in the world, was designed as "market entry assistance to allow for cost reductions, which will then facilitate the diffusion of photovoltaic through the market" (German Federal Diet, 1999). The \$5-10bn per year of US production tax credits for renewable electricity was enacted to enable "further advances of renewable energy technologies" (102nd Congress, 1992). And the US tax credit under the US 'Recovery Act' in 2009, with a total of \$7.5bn per year, had the objective "to help renewable energy technologies achieve economies of scale and bring down costs" (The White House, 2009).

Deployment policies are thus best understood as 'learning investments' (Sagar and van der Zwaan, 2006), rather than as static climate policy instruments. Indeed, if seen as static instruments to reduce current GHG emissions, most of current deployment policies are prohibitively expensive. At the beginning, the GHG abatement cost of the German support for solar power were as high as 760€ per ton of CO₂ (Frondel et al., 2008). This is orders of magnitude higher than the CO₂ emission allowance prices under the EU's Emission Trading Scheme, which provides a proxy for marginal abatement cost in the EU and has never exceeded 50€ per ton (since the end of 2012, they are below 10€; The WorldBank, 2012).

Broadly speaking, the motivation to fund large-scale deployment in order to advance technology is rooted in two empirical observations. First, numerous empirical studies suggest that the costs of a technology tend to correlate negatively with cumulative production, as captured in so-called experience curves (e.g., Wene, 2000). Figure 6 illustrates this widely observed phenomenon for a few examples from different sectors: electromechanical equipment (coal plants), biochemistry (ethanol), semiconductors (solar cells and transistors). A report in 1999 by the United States' President's Committee of Advisors on Science and Technology (PCAST) summarized this motivation in a report on energy technology policy:

"Once a technology has been demonstrated at a potentially commercially viable scale, there remains a long process of building a series of such systems to scale up equipment manufacturing facilities and also to learn how to reduce manufacturing, system installation, and operations and maintenance costs to competitive levels. ...

Many products, for instance, have costs that drop by 10-30 percent for every doubling of cumulative production. To move a new technology into the market, its higher initial costs relative to competing products must be covered. As cumulative production volume increases, costs will be reduced until some innovative energy technologies become fully competitive with conventional technologies.” (PCAST, 1999, ES-7).

Second, globally successful manufacturers of new technologies often emerge in countries that support deployment of these technologies early on, thereby creating ‘*home markets*’ that give domestic firms a lead in innovation (Beise-Zee, 2004). The Danish wind turbine industry, for example, benefited from an early home market that was supported by government policies, and maintained a large global market share even when domestic demand declined (Andersen, 2004). This and other success stories have motivated countries to pursue deployment policies in the energy sector (Mathews and Tan, 2014).

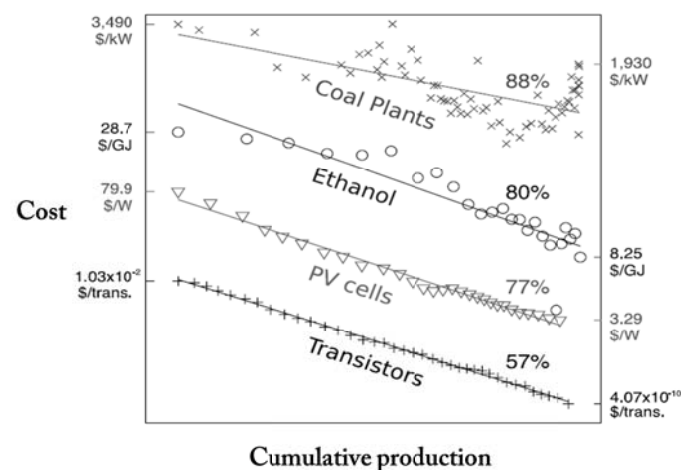


Figure 6: Empirical experience curves for different technologies (McNerney et al., 2011). Each curve was rescaled and shifted to aid comparison with a power law. Tick marks and labels on the left vertical axis show the first price (in real 2000 dollars) of the corresponding time series, and those of the right vertical axis show the last price. Lines are least-squares fits to a power law.

The new focus on deployment as a means to stimulate innovation represents a stark deviation from existing technology policy strategies, and reflects that governments are rethinking traditional models of technology policy in the context of global warming (Mowery et al., 2010). However, the theoretical understanding of the impact these learning investments has not kept pace with their application. There is relatively little academic research on deployment policies (e.g., Nemet, 2009; Peters et al., 2012; Bettencourt et al., 2013; Hoppmann et al., 2013, 2014). And those studies that have been done

present conflicting evidence (cf., Nemet, 2009; Bettencourt et al., 2013) and are scattered across academic (sub-) disciplines.

This dissertation assumes that the world is going to spend large sums of public resources on deployment policies in the energy sector, and aims to contribute to the understanding of how these policies can stimulate innovation. The objective is to facilitate better deployment policy design in the future.

3. Research Design

This dissertation addresses three overarching research questions that are rooted in the empirical challenges that policymakers face in the context of climate change. This section first puts these high-level research questions into context (3.1), and then explains the theoretical perspective and research framework adopted by this thesis (3.2 and 3.3). The specific research question and empirical strategy of each individual paper are introduced in section 3.4 and 3.5.

3.1. Overarching Research Questions

Governments plan to spend large sums of public resources on deployment policies to induce innovations in clean energy technologies, as described in section 2. In light of the magnitude of spending and the urgency of climate change, it is important that these public resources are spent effectively. The overarching research question of this thesis is therefore:

R0: How can deployment policies be designed in order to maximize their impact on innovation?

In broader perspective, the government-led creation of markets for innovative technologies in general is not new (Edler and Georghiou, 2007). Governments have long made use of demand-side measures to stimulate innovation, e.g., through targeted public procurement, tax incentives or mandates for the adoption of certain safety or environmental technologies (see Edler, 2013 for a comprehensive overview). But the recent use of deployment policies in the energy sector stands out in two important ways: the *scope* and *scale* of innovation that these policies aim to induce. This thesis aims to explore these two aspects in detail.

3.1.1. Accounting for Technological Characteristics in Deployment Policies

Deployment policies in the energy sector are used to stimulate innovation across a very broad scope of technologies through relatively standardized policy instruments. Unlike other sectors, such as chemicals or semiconductors, the energy sector is not defined by a specific field of knowledge. A huge variety of technologies from almost all sectors of the economy are employed in the extraction, conversion and end-use of energy. The actors in the sector itself, such as electric utilities, district heat providers or transport system operators often only develop relatively few technologies themselves (Markard, 2011; Wiesenthal et al., 2011).⁶ Rather, most energy innovations enter the sector embodied in specialized equipment or innovative fuels from supplying industries, such as semiconductors (solar cells), electro-mechanical machinery (gas turbines), agriculture (biofuel feedstock) and biochemistry (biofuel conversion). Some technologies are mass-produced (e.g., LEDs); others are large infrastructure systems (public transport systems). Some are very specific to local geographies, such as biofuel feedstock production techniques, while others are globally applicable almost without adaptation, such as the feedstock-to-biofuel conversion in bio-refineries. Deployment policies in the energy sector thus aim to stimulate innovation not in a narrowly defined industrial context, but across a wide range of sectors characterized by different knowledge bases, value chain structures and innovation processes (Malerba, 2002).

At the same time, most deployment spending is concentrated in a relatively limited number of policy instruments, some of which are used in a one-size-fits-all fashion. For example, fixed feed-in tariffs for renewable electricity alone account for more than half of projected deployment subsidies and are typically offered to all forms of renewable electricity. This differentiates deployment policies in the energy sector from public procurement instruments in, say, defense: there, technology is also sourced from a wide range of sectors, but procurement policies are typically designed in the form of contracts tailored to the characteristic needs of individual departments (Mowery, 2012). This thesis therefore aims to address the following research question:

RQ1: How can deployment policies be designed to account for technological characteristics?

⁶ In Pavitt's taxonomy, the energy sector is 'supplier-dominated' (Pavitt, 1984).

3.1.2. Ensuring Effectiveness over the Lifetime of Deployment Policies

Projections suggest that, in order to compete with fossil fuels, low-carbon technologies have to be supported over a long period of time, and eventually brought to very large scale. The projected scale of public spending on individual deployment policy instruments in the energy sector appears unprecedented, even by the standards of defense or space RD&D (see section 2.2), and creates two concrete challenges for the design and governance of deployment policies.

First, many deployment policies have a time horizon and thus aim to support innovation across many product and process generations as firms move down the experience curve, rather than targeting individual products such as; say, a new jet fighter or rocketship. Most energy products and services are commodities – e.g., fuels, electricity and heat – that allow for relatively little product differentiation. Therefore few self-sustaining niche markets exist and technologies have to be supported until they can compete on costs with fossil alternatives. The design of these policies needs to account for the fact that the technological and socio-economic risks and challenges that innovators face change over time as the supported technology evolves from a few small demonstration plants to the point where it is deployed throughout the economy (e.g., Jacobsson and Bergek, 2004). However, in most technology policy analyses, policy decisions are seen as essentially exogenous to the technological evolution that the intervention aims to induce.

Second, since investments in the sector are capital intensive and have long lifetimes, only relatively predictable policy support can have the desired impact on innovation. At the same time, as mentioned in section 2.2, deployment policies are typically expensive ways to mitigate carbon emissions in the near term, which makes the short-term cost of deployment policies very salient and controversial in the public debate. Their benefits in the form of innovation and long-term cost reductions, on the other hand, are inherently uncertain and difficult to determine, even in hindsight. For example, a recent report by the German government’s Expert Commission for Research and Innovation analyzed patenting in renewable energy technologies in Germany and came to the conclusion that “there is no measurable innovation impact” of the German support for renewable electricity (a 15-year old program that cost about \$20bn per year), which caused a stir in the media (E-FI, 2014, p. 15). A large group of renowned innovation researchers promptly replied with the statement that there is, in fact, plenty of evidence when looking at a broader range of indicators (Ragwitz et al., 2014).

The challenges created by large costs and intangible benefits are aggravated by the fact that most deployment policies are designed not as one-off grants, but as long-term subsidies for which any investment that fulfills certain technological criteria is eligible. Under these circumstances, if the policy is unexpectedly effective in attracting investments, large subsidy commitments over decades can be locked-in in only a few years (Frondel et al., 2009). Such cost overruns can be very difficult to correct. Several large deployment policies have been cancelled abruptly or retroactively changed because of such unpredicted cost developments. Prominent examples include the policy support for renewable power in Spain and the Czech Republic, where promised long-term subsidies were retroactively reduced, leaving investors with stranded assets. In other cases, deployment policy support was significantly reduced for new investments, leading to a steep decline in demand – e.g., in the case of the ‘California Wind Rush’ in the early 1980s or the German support for biomass power in 2014 – leading to bankruptcies of project developers, technology suppliers and service providers. Both scenarios put the policy’s long-term impact on innovation in question and risk the perceived and/or actual waste of scarce public resources. What’s more, since the investors’ cost of capital is affected by their and the lenders’ degree of trust in the policy, even the possibility of retroactive changes could prevent the deployment policy from attaining its targets cost-effectively.

In view of the need to design deployment policies that remain effective in inducing innovation at very large scale over the entire policy lifetime, it is important to understand how deployment policies can (i) adapt to changing support needs as the technology evolves, and (ii) be designed to minimize political uncertainty as well as the risk of declining legitimacy and retroactive changes. Therefore, the second overarching research question explores the implications for public policy design of the dynamic perspective on deployment policies:

RQ2: How can deployment policies be designed to ensure effectiveness over the lifetime of the policy?

3.2. Theoretical Perspective

To translate the overarching research questions into concrete schemes of analysis for the individual case studies, this thesis applies a theoretical perspective rooted in the field of innovation studies (Fagerberg and Verspagen, 2009; Fagerberg et al., 2012; Truffer et al., 2012). The theoretical concepts primarily employed here are related to (i) the *evolution of technology* and (ii) the broader *socio-technical system* in which this evolution is embedded. These two blocks of concepts inform how RQ1 and RQ2/3 are addressed, respectively.

3.2.1. Technological Evolution as Learning Process

Technological products are conceptualized in this thesis as *systemic artifacts* (Saviotti, 1986; Tushman and Rosenkopf, 1992), consisting of a non-trivial number of interdependent sub-systems and components. These sub-systems and components are organized by a *product architecture*, which allocates system functions to the individual components and defines the interfaces between them (Simon, 1962; Clark, 1985; Baldwin et al., 2014).

Apart from rare periods of competition between different architectures, *innovation* in technological products is understood as proceeding predominantly through the refinement within and extension of existing product architectures, in a cumulative and incremental *learning process* (Nelson and Winter, 1977; Dosi, 1982). Shaped by an understanding of important technological bottlenecks and promising avenues of solutions widely shared within the community of practitioners, the learning process focuses on only a small fraction of a product's components and possible directions of change at any point in time (Rosenberg, 1969; Hughes, 1992; Ethiraj, 2007; Dedehayir and Mäkinen, 2011). Other parts of the product – and, crucially, how the components work together – are retained essentially unchanged (Anderson and Tushman, 1990; Henderson and Clark, 1990; Murmann and Frenken, 2006). The resulting 'ordered' pattern of technical change is referred to as the *technological trajectory*. The process of technological learning along this trajectory involves numerous feedback loops between research, development, demonstration and deployment as firms experiment with new components and sub-systems (e.g., Kline and Rosenberg, 1986), which blurs the boundaries between invention, innovation and diffusion (Fleck, 1988).

This perspective implies that, in order to understand the role of technology deployment for innovation, it is essential to analyze the learning processes in different energy technologies including the nature of feedback loops between deployment on one side and research, development and demonstration on the other. More specifically, in order to address the question how deployment policies in the energy sector can be designed to account for technological characteristics (RQ1), this thesis analyzes how technological characteristics affect the (i) *sequences* in the process of learning (e.g., the early aircraft industry focused first the aerodynamic characteristics of the body, then on improving the engine); (ii) *type* of learning process (e.g., learning-by-doing, learning-by-using); and (iii) *spatial patterns* of learning (e.g., learning in local clusters of firms or learning in global communities of practitioners).

3.2.2. Dynamics in Socio-Technical Systems

Following the literature on innovation systems, technological evolution is understood here as embedded in *socio-technical systems*, formed by a large number of actors (e.g. firms, policymakers), networks (formal and informal), technologies (knowledge and artifacts) and institutions (e.g. norms, values or regulations) (e.g., Carlsson and Stankiewicz, 1991; Edquist et al., 2005). Accordingly, the ‘outcomes’ of technological evolution, i.e., the development, adoption and diffusion of technologies, are the result of dynamic interactions between the individual elements of the socio-technical system. These interactions are understood to be non-linear and to involve numerous externalities (positive and negative), thus giving rise to emergent system properties such as *bottlenecks* and *virtuous cycles* (Bergek et al., 2008; Negro et al., 2012).

From this perspective, deployment policies can play a crucial role in technological evolution whenever they help overcome bottlenecks and initiate virtuous cycles (Bergek et al., 2008; Wieczorek and Hekkert, 2012). However, at the same time, policy interventions and policy changes cannot be seen as entirely exogenous to the evolution of the socio-technical system (Kern, 2011; Meadowcroft, 2009, 2011; Scrase and Smith, 2009). On one hand, policy makers may hold differing opinions on what constitutes the most important bottlenecks and how to remove them (Meadowcroft, 2009). What is more, even if there is a political consensus regarding the goals and means of policy-making, the inherent complexity of socio-technical systems may limit the degree to which consequences of policy interventions can be accurately foreseen (Faber and Alkemade, 2011). On the other hand, the political legitimacy of continued policy intervention can erode over time in response to unforeseen or unpopular technological outcomes.

This thesis aims to inform the design of deployment policies that attempt to support technologies with large subsidies over decades and to bring technologies from small niche markets up to deployment throughout the economy. From the systems perspective outlined above, the degree to which deployment policies can be effective in supporting innovation over the lifetime of the policy (RQ2) depends essentially on two factors, which will be addressed in this thesis: whether they successfully *address the series of bottlenecks as the socio-technical system evolves*; and whether they *account for existing system structures* (including technologies, actors, networks and institutions) so as to maintain political legitimacy over the full lifetime of the policy intervention.

3.3. Contributions to the Literature

Each individual chapter makes a specific contribution to the literature on technological innovation and public policy. That said, there are two overarching contributions from the thesis as a whole to the literature on technology policy: (i) the explicit consideration of linkages between technological characteristics, learning processes and deployment policy impacts (related to RQ1), and (ii) the explicit consideration and anticipation of how technological change feeds back into the political process and affects policy decisions (RQ2).

The two contributions are illustrated in two figures below. Figure 7 shows the literature context of the papers addressing RQ1 as well as the contribution of this thesis. The figure illustrates that there are a number of studies that analyze the impact of deployment policies on technological invention and innovation (e.g., Nemet, 2009; Johnstone et al., 2010; Peters et al., 2012; Hoppmann et al., 2013). There are also several in-depth studies of learning processes in energy technologies (e.g., Wilson, 2012) and the relationship between learning processes and the impacts of technology policy in general, and deployment policies in particular (e.g., Norberg-Bohm, 2000; Winskel et al., 2014). However, there are only few studies that analyze how technology-level characteristics, such as the product architecture and the cost structure, affect learning processes and deployment policy impacts, which is the focus of the papers addressing RQ1.

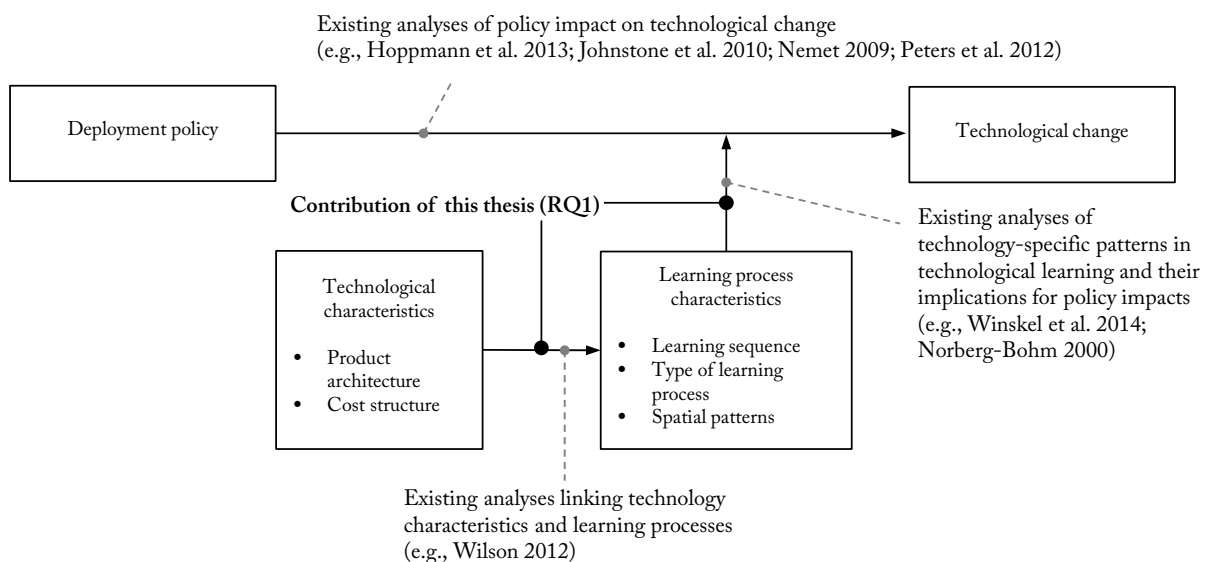


Figure 7: Unique contribution of papers addressing RQ1 to the literature and differentiation from existing analyses.

Figure 8 shows the literature context of the papers addressing RQ2 and the gap that this thesis addresses. Building broadly on the work of Lindblom on ‘muddling through’ (Lindblom, 1959), there

have been a number of studies in the political science literature of the dynamics of the policymaking process and *learning* on the side of policymakers (Bennett and Howlett, 1992; May, 1992; Sanderson, 2002). There have also been studies of the impact of deployment policies on broader socio-economic dynamics of technological systems, including the formation of actor coalitions and political legitimacy (Jacobsson and Bergek, 2004; Jacobsson et al., 2004), and the feedback of those impacts to the political process (Jacobsson and Lauber, 2005, 2006). However, there have been few studies that looked at the impact of *technological change* on the dynamics of policymaking in technology policy in general and deployment policies in particular.

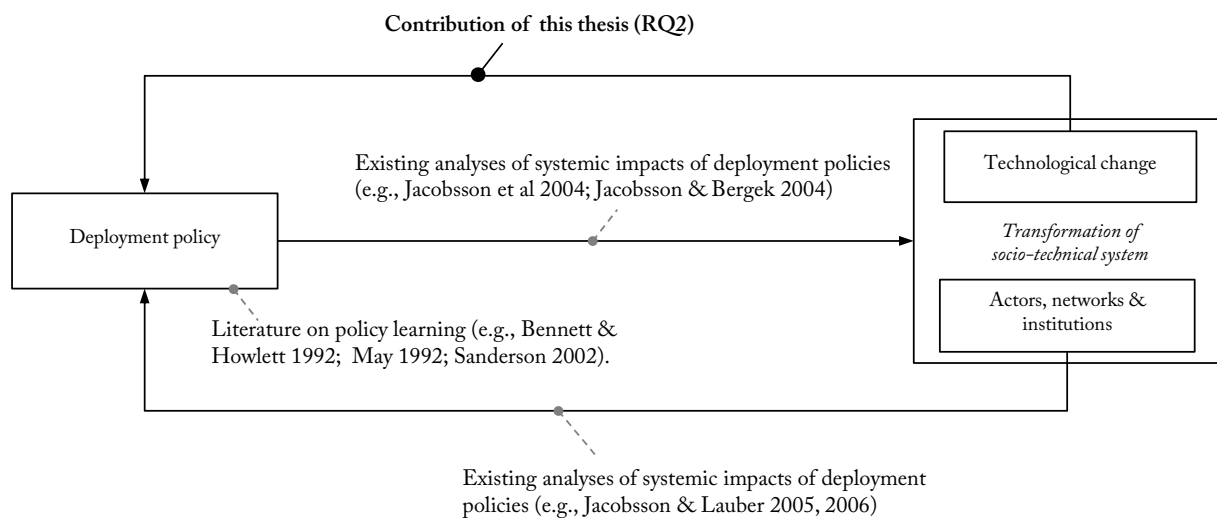


Figure 8: Unique contribution of papers addressing RQ2 to the literature and differentiation from existing analyses.

3.4. Research Framework and Contributions of Individual Papers

Figure 9 presents the research framework of this dissertation, indicating the main concepts and relationships. It merges Figure 7 and Figure 8, the two figures representing the contributions of RQ1 and RQ2. The focus of the individual papers is indicated by the numbers in brackets.

In the big picture, this thesis is concerned with the impact of deployment policies on technologies change, understood here as encompassing invention, innovation and diffusion. More specifically, this thesis aims to inform deployment policy design in view of technological characteristics (shown in the lower part of Figure 9) and the interplay between technological change and the policymaking process (upper part of Figure 9).

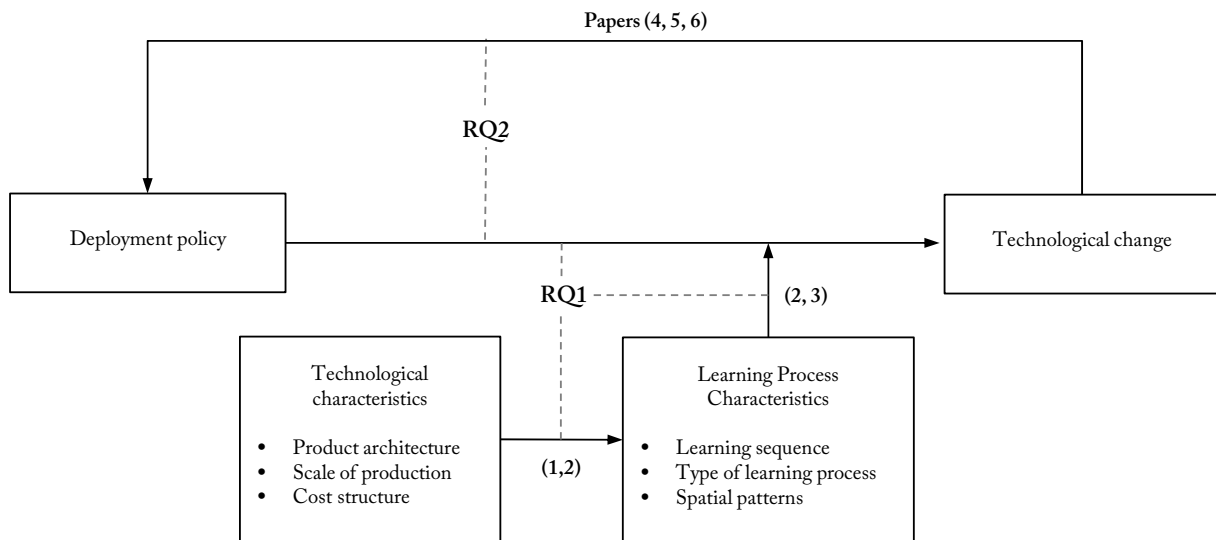


Figure 9: Research framework of this thesis, indicating main constructs and relationships. “RQ1” and “RQ2” mark the mechanisms analyzed to address the two overarching research questions. The focus of the individual papers is marked by the numbers in brackets.

The role of each of the six papers in the framework is summarized in Table 1. While there are a number of linkages and overlaps between the individual papers, the thesis is best understood as divided into two sets of three papers, where each set addresses one of the overarching research questions.

Papers 1-3 investigate the linkages between technological characteristics (in particular, the product architecture and cost structure of a technology), prevalent learning processes (sequences in learning, types of learning processes and spatial patterns of learning) and the role of deployment for technological change (RQ1). Paper 1 analyzes the evolution of wind power technology to draw conclusions about how technological characteristics affect the shape of the technological trajectory and the aggregate, industry-wide learning process. Paper 2 builds on the findings and methodology of paper 1 and compares the learning processes in two technologies (wind power and solar PV), drawing conclusions about the influence of technological characteristics on the role of deployment for innovation in different energy technologies. Paper 3 models the experience curve of six renewable energy technologies in a developing country in order to shed light on the impact of technological characteristics on (i) the importance of local and global learning and (ii) the role of local and global deployment for innovation.

Papers 4-6 are primarily concerned with the interplay over time between deployment policies and technological change, and the implications of such a dynamic perspective for deployment policy design (RQ2). Paper 4 maps the co-evolution of the German feed-in tariff policy for solar power and the supported socio-technical system over time and identifies feedbacks from induced technological

change to the policymaking process. Paper 5 models the cost drivers of renewable energy deployment policies in developing countries and discusses how the cost uncertainty can be anticipated and managed in order to enhance the effectiveness of such policies. Finally, paper 6 explores the lessons learned from the German feed-in tariff policy for solar power (paper 4) for the design of the new Japanese feed-in tariff policy.

Table 1: Overview of the six papers. Contribution of individual papers to overarching research questions is marked in column “RQ”.

#	Title	RQ	Role in Thesis / Framework	Research Case	Methodology
1	How a Product’s Design Hierarchy Shapes the Evolution of Technological Knowledge – Evidence from Wind Turbine Technology	1	Develops a methodology to analyze the impact of technological characteristics on the learning process in energy technologies and applies it to one specific case	Wind power (global)	Patent-citation network analysis, Qualitative patent content analysis
2	Technology Life-Cycles in the Energy Sector – Technological Characteristics and the Role of Deployment for Innovation	1	Applies the methodology developed in paper 1 to compare two energy technologies, and analyzes the impact of technological characteristics on (i) the learning processes in different energy technologies and (ii) the role of deployment policies for innovation	Wind power and solar PV (global)	Patent-citation network analysis, Qualitative content analysis
3	The Effect of Local and Global Learning on the Cost of Renewable Energy in Developing Countries	1	Analyzes the impact technological characteristics on (i) the importance of local and global learning and (ii) the role of local and global deployment for innovation	Six renewable energy technologies in Thailand	Techno-economic model
4	Compulsive Policy-Making – The Evolution of the German Feed-in Tariff System for Solar Photovoltaic Power	2	Analyzes the interplay between deployment policies and technological change, especially feedbacks from induced technological change to the policy process	Solar PV in Germany	Qualitative analysis of interview data, parliament debates and secondary sources
5	International Support for Feed-in Tariffs in Developing Countries – A Review and Analysis of Proposed Mechanisms	2	Builds on findings from papers 3 and 4 and demonstrates that the effectiveness of deployment policies in developing countries depends on uncertain future cost developments, and discusses how this finding can be translated into policy design	Six renewable energy technologies in Thailand	Techno-economic model
6	Japan’s Post-Fukushima Challenge–Implications From the German Experience on Renewable Energy Policy	2	Builds on the lessons learned in paper 4 and discusses how the effectiveness of deployment policies depends on Legitimacy stemming from domestic industry creation, and how this relationship can be managed in the case of Japan	Solar PV in Japan	Comparative analysis

3.5. Methodology

This thesis investigates the complex interplay between public policy and technological change from multiple perspectives. Given the complementarity of quantitative and qualitative methods, a combination of both is fruitful (Creswell, 2013) and can yield better results than an analysis based on a single method (Taylor et al., 2005).

Overall this dissertation employs four methodologies (see Table 1 above). Papers 1 and 2 integrate quantitative *citation-network analysis* with *qualitative content analysis* of patents into a novel methodology to study the evolution of technology. This methodology allows a quantitative analysis of the technology life-cycle and allows one to draw comparisons between energy technologies about importance of different learning mechanisms over time and the role of deployment in innovation. Papers 3 and 5 are based on a *bottom-up techno-economic model* of Thailand's Alternative Energy Development Plan, a deployment policy for six renewable energy technologies in the country's electricity sector. The model allows for the development empirically grounded estimates of the effects of various factors, including technological characteristics and different learning mechanisms, on the cost of achieving the targets.

The remaining two papers (4 & 6) employ qualitative methodologies. Paper 4 is based on a *qualitative case study* using interview and archival data (especially parliamentary debates) on Germany's solar power policy. Paper 6 explores some of the lessons learned in the work for Paper 4 in a *comparative study* of the socio-economic context for solar power in Germany and Japan.

4. Summary of the Papers' Findings

This section provides a brief summary of each paper's main findings, and explains how they build upon and relate to each other. Each paper's summary contains the implications that are relevant for the understanding of the other papers' findings. Broader policy implications that address the overarching research questions RQ1 and RQ2 are discussed in section 5.

4.1. Paper 1: How a Product's Design Hierarchy Shapes the Evolution of Technological Knowledge – Evidence from Wind Turbine Technology

Paper 1 analyzes the technological trajectory in wind turbine technology between 1973-2009 to shed light on the relationship between technological characteristics and the long-run dynamics of technological learning in energy technologies (Huenteler et al., 2014b). To do so, a novel methodology is developed that integrates tools from (i) network analysis and (ii) patent-content analysis. This method allows us to study the technological focus of inventions along the core trajectory of technological change in an industry. The paper's main findings center around the temporal pattern of innovation along a technological trajectory and its main determinants. In particular, the results demonstrate that the sequence of technological problems solved in an industry is not random, but a function of the *product architecture* and the *demanded functional characteristics* – i.e., a combination of supply-side and demand-side factors.

As an illustration, Figure 10 below shows inventive activity in different sub-systems of a wind turbine over time. It can be seen how the focus of inventive activity shifted from the rotor, which directly affects most functional characteristics (i.e., the 'core' sub-system), over time to more peripheral sub-systems (first power-train, then grid connection and mounting & encapsulation). Overall, it took a little over 20 years from the onset of large-scale deployment of wind turbines until the point when the focus of inventive activity had shifted through all sub-systems of the product architecture.

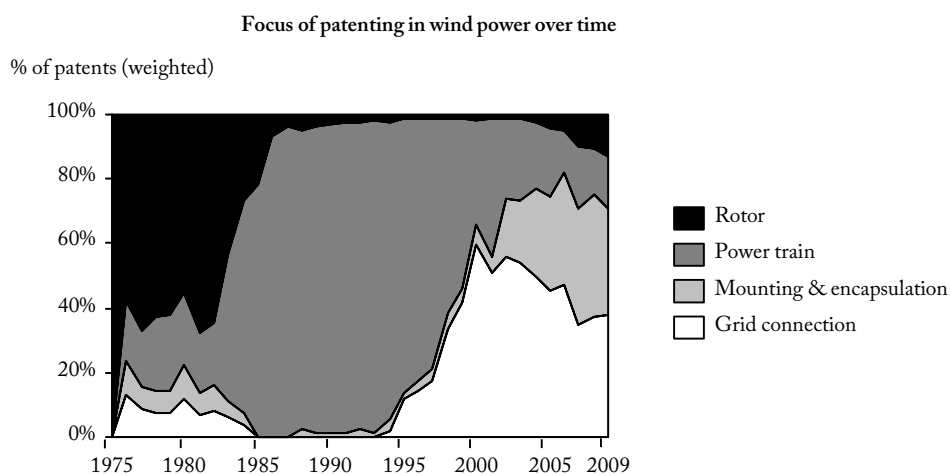


Figure 10: Focus of main patents in wind turbine technology, illustrating the shifting focus of inventive activity over time.

These findings have two important implications for the analysis of deployment policies. *First*, technological characteristics shape the temporal patterns of technological evolution. The design of

energy technologies with complex product architectures, such as wind turbines, *continues to evolve decades* after the onset of large-scale deployment, even if a dominant design has been reached for core sub-systems (such as the three-bladed rotor in the case of wind turbines). If designed appropriately, deployment of these technologies can subsequently unlock technological potentials by enabling continuous experimentation with novel sub-system and component designs, rather than simply induce cost reductions. This poses interesting questions for deployment policy design. In particular, how can large-scale subsidy schemes be designed to stimulate experimentation, encourage user-producer interaction and reduce technological uncertainty? Section 5.1 below discusses this question in detail.

Second, the demanded performance characteristics have a direct influence on the direction of technological evolution. This suggests that the *nature of demand* created through deployment policies matters for their impact on technological change at least as much as the *size of demand* (e.g., whether investors are incentivized to demand grid-friendly electricity or low cost). As described in section 2.2 above, most deployment policies aim to induce cost reductions by subsidizing learning and economies of scale because technological progress is seemingly mostly about cost reductions. For example, financial incentives for wind turbines in many countries are designed in a way that investors do not have to worry about the intermittency of wind power or the grid behavior more generally. These deployment policies miss out on opportunities to stimulate technological evolution in directions that might be beneficial in the long term, at least in the case of complex products such as wind turbines.

4.2. Paper 2: Technology Life-Cycles in the Energy Sector – Technological Characteristics and the Role of Deployment for Innovation

The second paper builds on the findings and the methodology from Paper 1 and presents a comparative analysis of the technological trajectories in wind power and solar PV (Huenteler et al., 2014c). The findings are related to the *temporal patterns* of learning as well as the predominant *type* of learning process (learning-by-doing, learning-by-using) along the technological trajectories.

In particular, the paper analyzes which of two common models of innovation over the *technology life-cycle* best describes the pattern of innovation in the two technologies. The results suggest that solar PV technology followed the life-cycle pattern of *mass-produced goods*, a model that typically applies to technologies with relatively simple product architecture and a large-scale production process: early product innovations were followed by a surge of process innovations, especially in solar cell production. Wind turbine technology, in contrast, more closely resembled the life-cycle of *complex products and*

systems, a model that has been developed for technologies with a complex product architecture and low-volume production: the focus of innovative activity shifted over time through different parts of the product, rather than from product to process innovations.

The results are based on an analysis of the ‘critical path’ of the patent-citation networks (a proxy for the main trajectory of technological development) in the two technologies over the period 1963-2009. Figure 11 below shows how the critical paths of the two technologies shift over time from product to process focus (solar PV, on the left) and through different parts of the system (wind power, on the right).

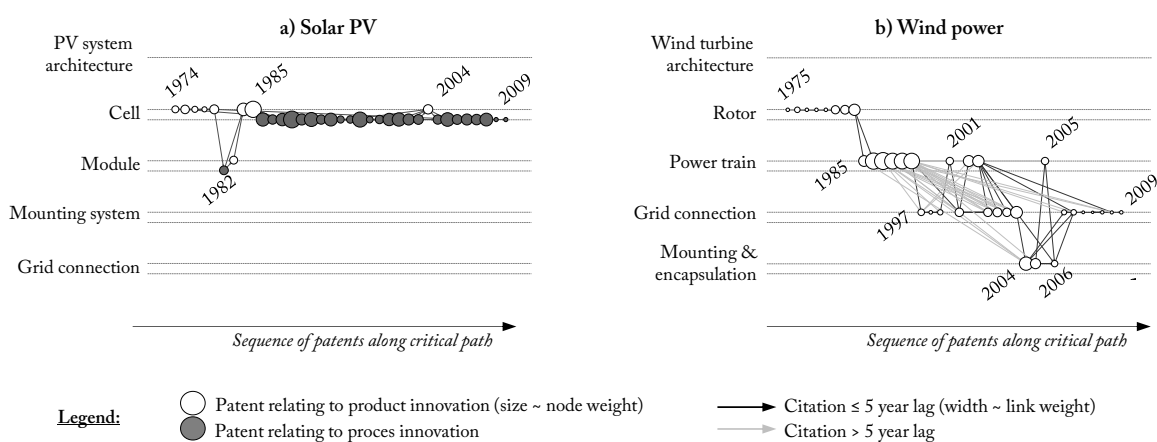


Figure 11: Focus of innovative activity in solar PV and wind power along the technological trajectory.

The findings have implications for the patterns of technological learning in energy technologies from the general literature on technology life-cycles. In solar PV, most innovations after the first large-scale deployment of the technology in the 1980s were focused on the production process, which points to a predominant role of *learning-by-doing*, *economies of scale* and *innovations in production equipment*. In wind power most innovations introduced novel sub-system and component designs, which highlights the importance of *learning-by-using*, *technology up-scaling* and *innovations in operation & maintenance* (O&M). These differing patterns correspond well with existing studies of technological learning in the two technologies and help to put these studies in comparative context.

The contrasting characterizations of the learning processes in the two technologies suggest that deployment policies play very different roles in innovation in the two technologies: in a learning process that is centered on the production process, deployment policy support can be crucial to enable learning-by-doing, large-scale production and markets for production equipment. In contrast; in a learning process that is centered on the product design, deployment policy support can be crucial to

enable learning-by-using, gradual up-scaling and markets for specialized O&M service providers. What these differing roles of deployment policy support mean for the design of policy instruments is discussed in section 5.1 below.

4.3. Paper 3: The Effect of Local and Global Learning on the Cost of Renewable Energy in Developing Countries

The third paper focuses on the relationship between technological characteristics and the *spatial patterns* of technological learning of different energy technologies in advanced developing countries (Huenteler et al., 2014a). The paper presents a quantitative case study of Thailand Renewable and Alternative Energy Development Plan (AEDP; 2013-2021). In particular, it develops a model of Thailand's electricity sector to estimate the relative contributions of local and global learning to cost reductions in six renewable electricity sources supported under the AEDP and analyzes the differences between the technologies.

Figure 12 illustrates the three main findings of the paper. The different bars show projections for the cost of electricity in 2021, in c\$ per kWh, for 6 renewable and 8 fossil generation technologies. For each renewable energy technology, four bars depict the results of four different model specifications: one without any technological learning over the lifetime of the policy (2013-2021), one with only local learning, one with only global learning and one with both.

First, technological learning can, in the near future, reduce the cost of renewable electricity in emerging economies to a level that is close to competitiveness with fossil fuels. *Second*, in aggregate, the largest potential for cost reduction lies in local learning. This finding lends quantitative support to the argument that the conditions enabling local learning, such as a skilled workforce, a stable regulatory framework, and the establishment of sustainable business models, have a more significant impact on cost of renewable energy in developing countries than global technology learning curves. The recent shift of international support under the UNFCCC toward the strengthening of local innovation systems is therefore promising. *Third*, relative importance of local and global learning differs significantly between technologies. The results show that local learning is most important, in relative terms, for micro hydro, biogas and biomass. Global learning is most important for solar PV, concentrating solar and wind power.

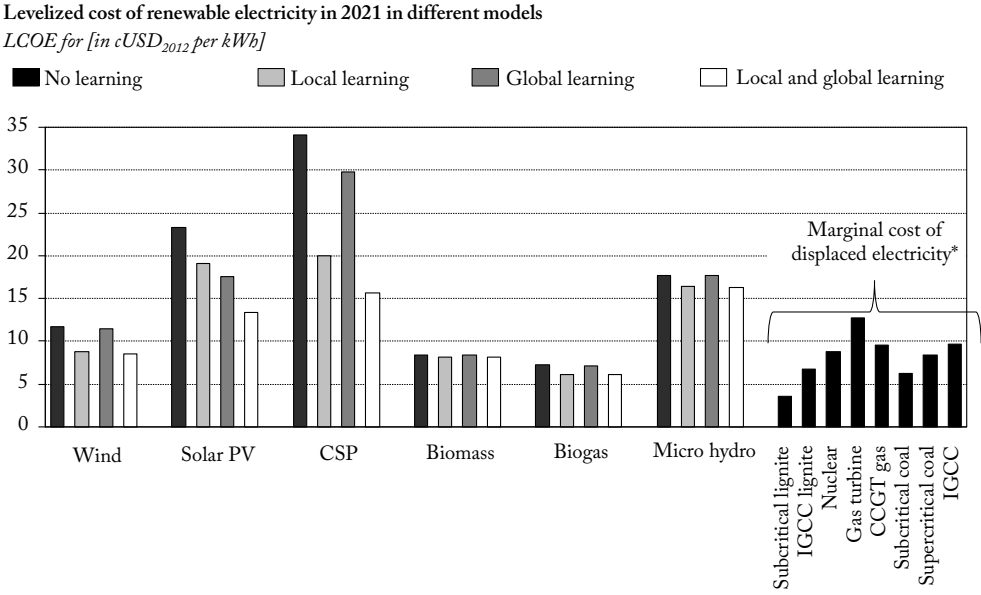


Figure 12: Impact of local and global learning on the cost of renewable electricity technologies under Thailand’s Alternative Energy Development Plan. The four different bars for the six renewable energy technologies represent different models.

The results for the relative impact of local and global learning depend on assumptions about how much of the technology is manufactured locally. To obtain realistic estimates for the spatial patterns of learning, the paper compiled typical cost splits between locally and globally sourced components for the six technologies in an advanced developing country like Thailand (shown in Table 1). The estimates suggest that the relative contributions of local and global learning are affected by technological characteristics, in particular the product architecture and the cost structure, which affect the share of components and services that can typically be manufactured locally: All components and services that require a high share of localized knowledge (say, about local geography or regulations), are produced in very small volumes or costly to transport are typically sourced locally. Only those components and services that are relatively standardized *and* large-scale in production are sourced globally.

Table 2: Split between locally and globally sourced components for the six analyzed technologies.

Technology	Locally sourced parts	Globally sourced parts	Cost split (local/global)	Learning rate (local/global)
Wind	Grid connection; engineering; procurement & construction; foundation; rotor blades; tower	Nacelle (including electrical machinery, power electronics & control system)	67%/33%	11.3/4.3
PV	Grid connection; engineering; procurement & construction; balance of system excluding inverter	PV modules; inverter	43%/57%	17/20
CSP (solar tower)	Grid connection; engineering; procurement & Construction; solar field	Power block; heat transfer fluid cycle	67%/33%	14.6/14.6
Biomass (anaerobic digestion)	Grid connection; engineering, procurement & construction; fuel shredder; boiler; heat exchanger; piping	Steam turbine and electric generator (prime mover); flue gas and water treatment	75%/25%	5/5
Biogas	Grid connection; engineering, procurement & construction; fuel handling; balance of system; 75% of converter system	Gas engine (prime mover); 25% of converter system	78%/22%	5/5
Micro hydro	Grid connection; engineering, procurement & construction; 50% of electro-mechanical equipment	50% of electro-mechanical equipment	87%/13%	5/5

For sources, see Paper 3.

Similar to papers 1 and 2, this paper's findings suggest that optimal deployment policy design can look very different for different energy technologies. The characteristics that determine local and global sourcing are very similar to the characteristics that affect the technology life-cycle pattern, as discussed in Paper 2. In general, *mass-produced goods*, with low architectural complexity and a high scale of production, such as solar PV, fuel cells or LEDs, will have a higher share of globally sourced components and services and benefit more from global learning effects. *Complex products and systems*, on the other hand, with high architectural complexity and low scale of production, tend to benefit more from local and regional learning effects. How these spatial patterns of learning translate into implications for deployment policy design is discussed in section 5.1 below.

4.4. Paper 4: Compulsive Policy-Making – The Evolution of the German Feed-in Tariff System for Solar Photovoltaic Power

Paper 4 analyzes the interplay between policy design and technological change to shed light on the long-term dynamics of deployment policy interventions (Hoppmann et al., 2014). It presents a case study of the German feed-in tariff system for solar power in the period 2000-2012, a highly effective and widely copied policy instrument targeted at fostering the diffusion and development of renewable

energy technologies. The analysis demonstrates that the policy has been subject to a considerable amount of changes, many of which are the result of policy makers addressing specific system issues and bottlenecks. Interestingly, however, often these issues themselves were driven by unforeseen technological developments induced by previous policy interventions.

A key motivation for enacting the German feed-in tariff for solar power in 2000 was to stimulate technological change in PV technology by enabling firms to enter the stage of mass production. However, over the 12 years that followed, the technology evolved in several ways that were not foreseen by the designers of the policy. *First*, the number of PV installations increased much faster than expected, culminating in debates about the costs connected to technology support that had to be borne by electricity consumers. *Second*, costs of PV technology fell at a considerably higher rate than predicted and resulted in windfall profits for both producers and users of PV technology. *Third*, especially in recent years, increasing deployment of PV has raised concerns about the stability of distribution grids and the longer-term integration of renewable sources into the electricity market. *Fourth*, while initially the German industry performed well, in recent years, a strong Chinese industry has emerged that markets its products in Germany, thereby directly profiting from the demand-side subsidies put in place.

The German government responded to each of these issues by implementing legislative or administrative changes to the feed-in tariff policy. These responses were often successful in resolving the immediate bottleneck, e.g., reducing windfall profits, and have been crucial in sustaining the effectiveness and political legitimacy of the German feed-in tariff policy, until it was essentially abolished in 2014. But they proved inadequate to mitigate foreseeable but less urgent issues. In fact, the analysis shows that, in many cases, policy interventions often triggered changes in the socio-technical system that – through complex system interdependencies – led to the emergence of new issues. The more momentum the socio-technical system gained, the more unforeseen technological developments exerted direct pressures on policy makers to adjust the design of previously implemented policies. In this sense, technological change served as both an outcome and a driver of policies targeted at inducing technological progress.

Based on the case study, the paper develops a descriptive framework of the cyclical interplay between policy design and technological change, based on Rosenberg's (1969) 'compulsive sequences' in the development of technical systems. The framework, labeled 'compulsive policymaking' (shown in Figure 13 below), stresses the role of the dynamics and uncertainty of technological change and

describes how these factors affect deployment policy interventions. The implications of this framework for the design and governance of deployment policies is discussed in section 5.2 below.

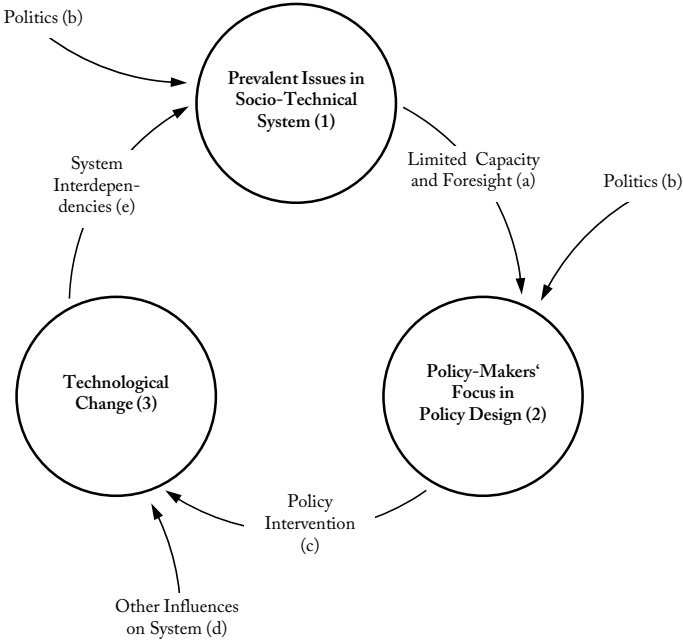


Figure 13: The descriptive model of the cyclical interplay between policy design and technological change, labeled ‘compulsive policymaking’.

4.5. Paper 5: International Support for Feed-in Tariffs in Developing Countries – A Review and Analysis of Proposed Mechanisms

Government support, in the form of feed-in tariff policies (FITs) for renewable electricity, has attracted large private-sector investments in sustainable electricity generation in the industrialized world (such as in Germany, as discussed in Paper 4). In an effort to replicate these experiences globally, a number of international organizations, NGOs, banks and donor countries are proposing mechanisms to cover part of the cost of FITs in developing countries. Paper 5 reviews these proposals for *supported FITs* and then uses a techno-economic model of Thailand’s Alternative Energy Development Plan 2013-2021 to analyze how feed-in tariffs (FITs) in developing countries can be supported through direct international financial assistance (Huenteler, 2014). A particular emphasis is placed on how policy design can ensure the long-term stability and effectiveness of such a policy.

Four main conclusions can be drawn from the analysis. *First*, the magnitude of the incremental cost of supported FITs is considerable. In the case of Thailand, the incremental cost of the FIT was estimated at USD 21bn or 3.15% of Thailand’s GDP in 2012. *Second*, the incremental costs of supported FITs in

developing countries are very uncertain (e.g., depending on the fossil fuel price scenario the FIT may result in a cost of USD 22bn or savings of 31bn; see Figure 14). *Third*, the uncertainty in the incremental cost is driven, to a large extent, by the uncertain savings from avoided fossil fuel consumption. This is mostly due to the nature of the uncertainty. Unlike the payments to the supported renewable electricity generators, which are uncertain but can be managed by carefully designing the process in which commitments are made, the avoided cost uncertainty is resolved only over the lifetime of the supported projects. Fuel prices may vary substantially over the 10-20 years that FIT payments have to be committed, and changes over time in the type of displaced electricity may result in large step changes in the avoided cost. *Fourth*, the paper shows that the reviewed proposals for internationally supported FITs differ in how they allocate the avoided cost uncertainty between national governments and international donors – some proposals assign all cost uncertainty to the national government, whereas the international side assumes all uncertainty in others.

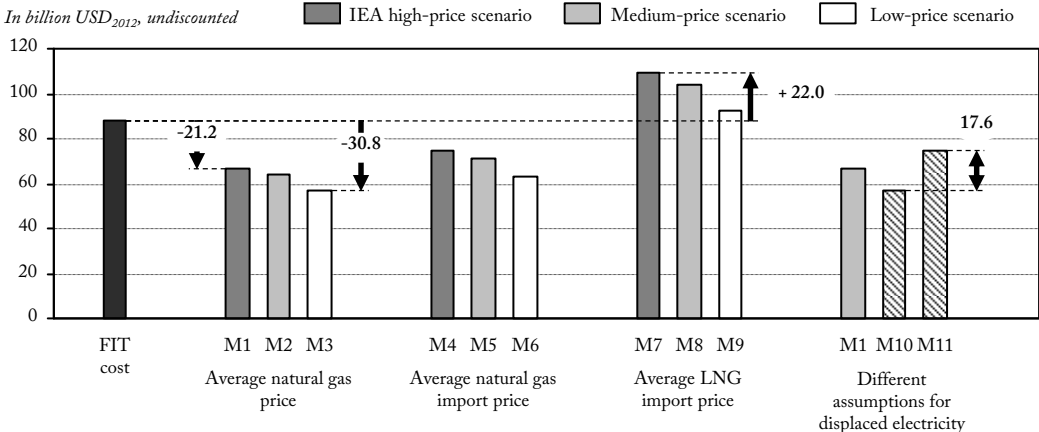


Figure 14: Avoided and incremental cost of a supported FIT in Thailand under different assumptions about fossil fuel cost scenarios and type of avoided electricity.

These findings have implications for the design of deployment policies in developing countries. *With regard to supported FITs*, the considerable uncertainty about policy cost implies challenges for the design and implementation of a supported FIT: donor countries will be unwilling to commit to financial assistance flows without knowing their eventual volume, while investors will only be attracted with a clear, long-term support commitment. This suggests that an international support mechanism that differentiates the allocation of uncertainty depending on the income level of the recipient country is more suitable for global-scale support than a one-size-fits-all approach: while emerging middle-income countries can be expected to absorb this risk, international donors might be willing assume it when they support the least-developed countries. *More generally*, Paper 5 offers valuable lessons for

governments in developing countries who aim to adopt specific deployment policy instruments that have proven successful in the developed world (see section 5.2).

4.6. Paper 6: Japan’s Post-Fukushima Challenge – Implications from the German Experience on Renewable Energy Policy

Paper 6 describes some important lessons learned from the support of solar PV in Germany (see Paper 4) and discusses their implications in the context of Japanese solar policy after the Fukushima accident (Huenteler et al., 2012). As in paper 5, a particular emphasis is placed on how policy design can ensure that the policy remains stable and effective in the long term.

The paper first highlights the main challenges to Germany’s FIT. *First*, since about 2008, the mounting payment commitments of the scheme have fuelled a public and scientific debate about the scheme’s future (PV accounted for only 3% of electricity production while cumulative committed payments reached approximately €100bn in 2011). *Second*, evidence suggests that the generous FIT incentivized firms to reallocate resources to new production capacity and, in relative terms, away from R&D, which led to a declining R&D quota (see Figure 15 below). *Third*, as an industrial policy, Germany’s FIT was largely unsuccessful, as illustrated by the rising imports in Figure 15. Because of these factors, the legitimacy of support for PV eroded over time (eventually leading to the abolishment of the FIT in 2014).

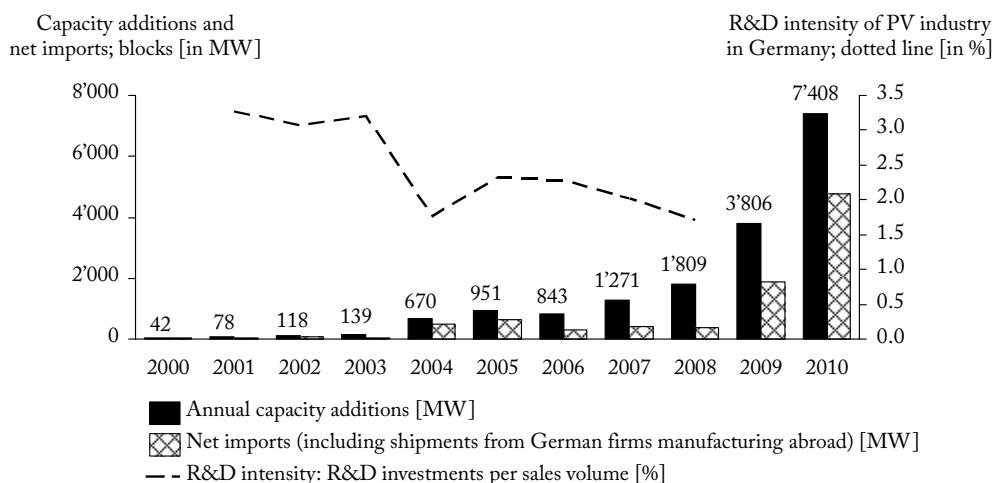


Figure 15: Main challenges for legitimacy of the FIT for PV in Germany: installations and net imports are growing exponentially while the research intensity in the industry is declining. For sources, see Paper 6.

Further, the paper discusses these challenges in the context of Japan’s new FIT policy for solar PV. It argues that concentration of regulatory authority for energy policy in the Ministry of Economy, Trade

and Industry renders economic and industrial policy aspects of the FIT particularly important. Whenever plans for the Japanese energy sector and the diffusion of renewables have been drafted, they prominently featured industrial policy objectives. The new FIT, too, lists “promotion of the domestic industry, and thereby strengthening the international competitiveness of [Japan]” as one of its main targets. At the same time, changes in the global industry landscape might make it difficult for Japan to achieve such objectives. The growth of the global market allowed huge production capacities to be built up, increasingly located in low-wage countries. The cost and scale advantage of Chinese/Taiwanese firms poses a significant challenge for their Japanese counterparts.

The paper derives three implications. *First*, in the long run, the government should strive for an integrative policy framework, balancing priorities of energy security, environmental policy, climate policy, as well as economic and industrial policy. A process of ‘policy learning’ and refinement, as achieved in Germany over the last 10 years, is only possible under a political framework with balanced responsibilities. *Second*, institutionalizing a FIT revision process that involves several ministries, such as for the German FIT, could enhance transparency of the political process. *Third*, given its current political situation, Japan should aim to maintain policy legitimacy by fostering both rapid cost reductions *and* industrial competitiveness. The focus on market subsidies rather than research funding in Germany appears to have created incentives to favor manufacturing and scale effects over long-term research. One way forward could be to make FIT support conditional on efficiency criteria in order to incentivize both diffusion and investment in long-term R&D. A modified FIT could, for instance, require solar modules to fulfill a condition similar to one that had been implemented in an investment subsidy that was granted to residential systems in 2009: in order to receive the subsidy, conversion efficiency had to exceed the average on the market. 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.

5. Conclusions

Two sets of overarching conclusions can be drawn from the six papers of this thesis. The first set of conclusions relates to the question of how deployment policies in the energy sector can be designed to account for technological characteristics (RQ1; section 5.1). The second set of conclusions addresses

the way in which deployment policies can be designed to ensure effectiveness over the lifetime of the policy (RQ2; section 5.2).

5.1. Tailoring Deployment Policies to Specific Energy Technologies

Few scholars would support a 'one-size-fits-all' technology policy approach for semiconductor, machinery, biotechnology, oil and gas, and chemical industries. This thesis' results indicate that it is equally misguided to lump together PV cells, wind turbines, biomass gasification, carbon capture and storage, and fuel cells when designing technology policy instruments. If the trillions of USD of public expenditures for deployment policies over the coming decades are to stimulate innovation effectively, their design needs to reflect the characteristics of the supported technologies.

5.1.1. Implications for Deployment Policy Design

The results presented in the first three papers demonstrate that technological characteristics – in particular, the product architecture, the cost structure and the scale of the production process – shape the *temporal* and *spatial* patterns of technological learning in energy technologies.

In terms of *temporal patterns*, the results suggest that the design of energy technologies that exhibit the characteristics of *complex products and systems* (complex product architectures and low production volume) continues to evolve over decades after the onset of large-scale deployment. In *mass-produced* energy technologies, the focus of most innovative activity is on the production process soon after the technology is deployed at scale. The two different patterns of learning imply different roles for deployment policies in the innovation process, and therefore have implications for deployment policy objectives and design, which are discussed below.

When going beyond the technologies analyzed in this thesis, it quickly becomes clear that the dichotomy of 'complex products and systems' and 'mass produced technologies' alone does not suffice to describe the full variety of energy technologies. Therefore, and given the continuous nature of the two determinants, the two life-cycle patterns are best understood as a continuum, as shown Figure 16. The higher the complexity of the product architecture and the smaller the scale of the production process, the more the policy implications of complex products and systems apply, and vice versa.

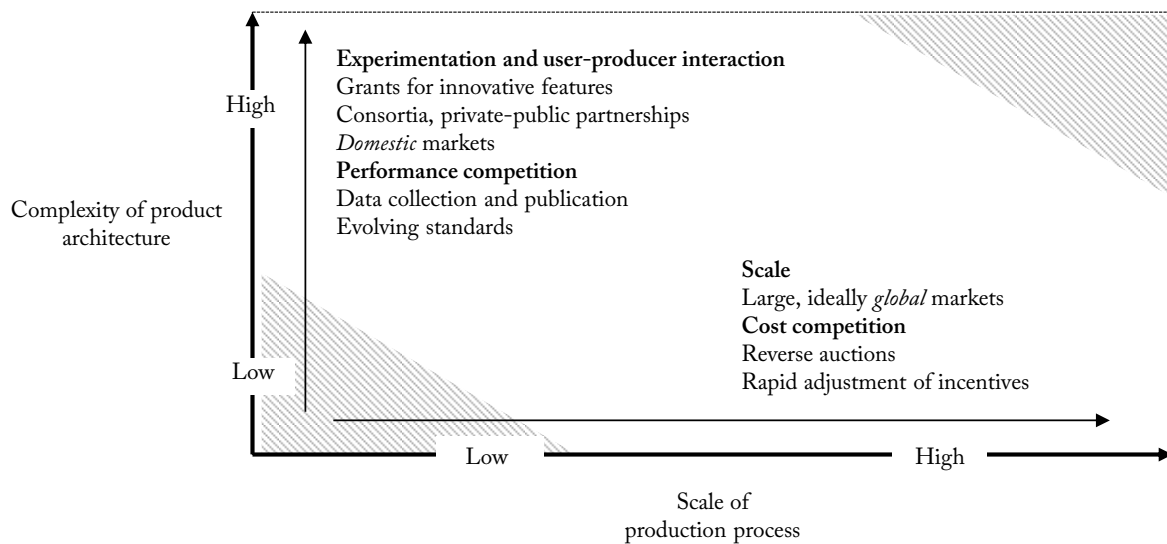


Figure 16: Objectives and design features of deployment policies for different types of energy technologies.

Deployment policies for technologies with a *complex product architecture*, such as wind turbines, geothermal systems, nuclear power plants, and tidal energy systems, deployment policies have to go beyond simply subsidizing scale in order to fully realize their potential innovation impact. For these technologies, deployment policies need to be understood as R&D policies rather than merely as subsidies. Simply doing ‘more of the same’ will not stimulate innovation in these technologies. Rather than enabling economies of scale, deployment policies should be targeted at creating ‘performance-driven’ niche markets (Grubler and Wilson, 2014): they should not aim for very large roll-out of existing technologies, but be explicitly be targeted at reducing technological uncertainty. For example by providing grants for innovative technology features, technology platforms, public-private partnerships, or by financing experimentation in different geographical and climatic environments. Furthermore, deployment policies could be accompanied by measures to enhance user-producer interaction (e.g., technology platforms or grants for consortia), improve market transparency (through collecting and publishing performance data) and gradually adjust performance standards (e.g., as it has been done with grid-integration requirements for wind turbines).

Deployment policies for *mass-produced technologies*, such as solar PV, in contrast, need to be understood as means to create conditions for large-scale production. Large markets, ideally coordinated internationally, are needed to enable the necessary economies of scale and the learning-by-doing in production. At the same time, policy support needs to make sure that cost competition remains high, e.g., by auctioning off subsidies, or by requiring benefiting companies to reveal production cost data and adjusting incentivizes continuously.

From a *spatial perspective*, markets for mass-produced goods should ideally be supported globally, both because of the necessary market scale and because there are significant free-rider effects for countries that wait and deploy later. Markets for *complex products and systems* should be supported on a regional or national level to reap the benefits of learning, because a patchwork of small niche markets will not overcome the ‘chicken and egg’ problem of low production volumes and high production cost.

Figure 17 locates a broader set of energy technologies in the technology space generated by the two characteristics. Complex products and systems are further divided into *infrastructure systems* (such as public transport systems and electricity grids) and *design-intensive products* (which include most large electric power plants). Infrastructure systems refer to technologies that are highly complex and are provided through a project-based production process, and thus involve hardly any process innovation. Design-intensive products are produced in small but significant quantities and thus involve some form of process innovation. On the other end of the spectrum, mass-produced technologies are divided into *continuous-flow processes* (such as transport fuels), for which the process is the primary focus of innovation from beginning, and *process-intensive products*, which involve some experimentation with different product designs in the beginning. The graphic also shows two groups of technologies that do not fit on the continuum between mass-produced technologies and complex products and systems: (i) *low-tech products* (small wind, small hydro turbines) which are relatively simple and produced in very small batches, and have potential for neither significant product nor process innovation, and (ii) *mass-produced complex products* (electric cars, grid-scale batteries), which involve continued product and process innovations over the entire technology life-cycle.

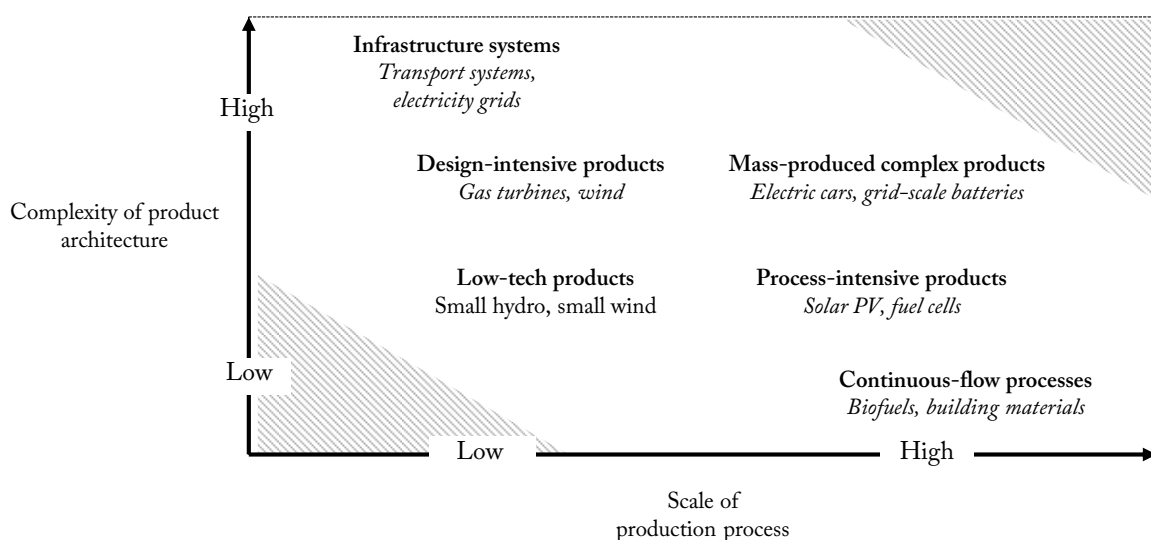


Figure 17: Stylized classification of different energy technologies according to scale of production process and complexity of product architecture.

5.1.2. Implications for Countries' Technology Strategies

Besides the *design* of deployment policies, the spatial patterns of technological learning also have important implications for the *choice of technologies* that countries support. This is particularly important for developing countries, which aim to attract local manufacturing but have only limited public resources to support the deployment of innovative energy technologies. Possible strategies for design-intensive and process-intensive types of technologies and three country types (low-, middle-, or high-income country) are listed in Table 3.

In *complex products and systems*, low- and middle-income countries have opportunities in the supply of components, such as mirrors for concentrating solar power plants (North Africa), parts for geothermal power plants (Indonesia) or towers for wind turbines (South Africa), which are often costly to transport. If the domestic market is large enough, prolonged experience with the supply of components for local projects may give firms a competitive edge that may lead to exports into other developing countries. Another field for domestic engagement for low- and middle-income countries is operation and maintenance, which can often become a significant share of value-add for design-intensive technologies. Middle-income countries may go beyond that and, with persistent domestic support over a long time, even become competitive system integrators in global markets, as both China and India are demonstrating in wind energy, and China in the field of large hydropower. To become competitive in the global market for final products, domestic firms need to engage in state-of-the-art technological activity over extended periods of time. That requires either early entry into the global market or very persistent domestic policy support. Likely only a few large countries outside the developed world (e.g., China or India) can afford such technology strategies.

Table 3: Technology strategies for different income-classes of countries.

	<i>Activity of domestic firms in...</i>		
	Low-income country	Middle-income country	High-income country
Design-intensive energy technologies	Peripheral components, operation and maintenance	Components, installation, operation and maintenance	System integration, core components
Process-intensive energy technologies	Installation	Simple production steps, installation and/or Production and export	Manufacturing equipment

In *mass-produced products*, much of the required know-how for manufacturing can be acquired by purchasing production equipment from advanced economies (technology transfer in the semiconductor,

textile, and consumer durables industries took this path, for example). If they have access to large export markets, firms in middle-income countries can become globally competitive, since they often face lower unit costs in terms of labor and energy. Becoming a manufacturing hub for technologies such as solar PV, solar heating (vacuum tubes), heat pumps, energy-saving building materials, or energy-efficient lighting might thus be a suitable strategy for middle-income countries with access to large domestic or global markets (in the field of solar PV, Malaysia, the Philippines and especially China are recent successful examples). High-income countries often focus on the export of manufacturing equipment related to these technologies. Low-income countries, on the other hand, have neither components to focus on (since the products are rather simple and often small in size), nor the opportunity to engage significantly in operation and maintenance (which is usually rather simple and takes a small share of value-add).

5.2. Designing Deployment Policies that are Effective in the Long Run

The results presented in the second half of the thesis have three important implications for the design of deployment policy interventions.

First, the findings suggest that a critical task in designing effective policies targeted at fostering technological change lies not only in developing adequate policy instruments based on existing knowledge about the technology but also in investing resources into *monitoring* and *understanding* the technological dynamics of the system to be intervened in. The study stresses the potential that lies in developing a profound knowledge about processes related to technological change and leveraging this knowledge when designing corresponding policies. For example, according to learning curve theory, cost reduction in solar PV technology is a function of deployment, but German policy makers chose a degression mechanism that reduced the remuneration for newly installed plants as a function of time, which turned out to be inadequate when the rates of deployment grew exponentially. A more profound understanding of the dynamics underlying cost reductions at the time of policy development might have prevented many of the iterations we have seen. To be sure, due to the complex nature of socio-technical systems it is by no means possible to accurately foresee the outcome of policy interventions based solely on the analysis of historical cases. Therefore, we suggest making system analysis an integral part of policy monitoring. Rather than only tracking the outcome of policy interventions, policy makers should try to understand the root cause of unexpected technology dynamics and their relation to policy.

Second, the analysis also has implications for policy makers who wish to adopt policy instruments that are already successfully used in other countries. Our study shows that the effectiveness and appropriateness of policy instruments at any given time is at least partly conditional on previous policy interventions and resulting changes in the socio-technical system. This implies that, although policy makers should leverage the lessons learned in other countries, there is a limit to which policy features implemented in other countries can be successfully copied. For example, the diffusion of solar PV in the German socio-technical system may now have built up enough momentum, e.g., in the form of trust in the system and vested interests, that the system can wither policy interventions aimed at increasing the cost effectiveness or grid-friendliness of the policy support. Introducing measures such as the mandatory direct marketing of renewable power in a nascent system without the same history of PV deployment may not show the same positive effects as in the German context as they may induce investment uncertainty and derail the deployment of the technology before it has even picked up momentum.

6. Overview of the Papers

The six papers that form this thesis are included in the following chapters. They are included either as published by the journal or as submitted to the journal. Five of the six papers are co-authored. For each of these papers, Table 4 below lists the co-authors and their respective contribution. The submission status of the papers is as of November 30, 2014.

Table 4: Overview of the six papers included in this dissertation.

#	Title	Authors	Authors' contribution	Status / Journal
1	How a Product's Design Hierarchy Shapes the Evolution of Technological Knowledge—Evidence from Wind Turbine Technology	Joern Huenteler, Jan Ossenbrink; Tobias Schmidt, Volker Hoffmann	JH and TS developed the model, JH and JO prepared the data, JH conducted the analysis and interpreted the results, JH, JO, TS and VH wrote the paper	Under review at <i>Research Policy</i> since 11/07/2014.
2	Technology Life-Cycles in the Energy Sector – Technological Characteristics and the Role of Deployment for Innovation	Joern Huenteler, Tobias Schmidt, Jan Ossenbrink; Volker Hoffmann	JH and TS developed the model, JH and JO prepared the data, JH conducted the analysis and interpreted the results, JH, JO, TS and VH wrote the paper	Working paper to be submitted to <i>Technological Forecasting and Social Change</i> .
3	The Effect of Local and Global Learning on the Cost of Renewable Energy in Developing Countries	Joern Huenteler, Christian Niebuhr, Tobias Schmidt	JH, CN, TS developed the model, JH conducted the analysis and interpreted the results, JH and TS wrote the paper	In press, <i>Journal of Cleaner Production</i> .
4	Compulsive Policy-Making—The Evolution of the German Feed-in Tariff System for Solar Photovoltaic Power	Joern H. Hoppmann, Joern Huenteler, Bastien Girod	JHH and JH developed the model, JHH conducted the analysis, JHH, JH and BG interpreted the results, JHH, JH and BG wrote the paper	Published in <i>Research Policy</i> 2014, 43 (8), p. 1422-1441.
5	International Support for Feed-in Tariffs in Developing Countries—A Review and Analysis of Proposed Mechanisms	Joern Huenteler	JH, CN, TS developed the model, JH conducted the analysis and interpreted the results, JH wrote the paper	Published in <i>Renewable and Sustainable Energy Reviews</i> 2014 (11), 39, p. 857–873.
6	Japan's Post-Fukushima Challenge—Implications From the German Experience on Renewable Energy Policy	Joern Huenteler, Tobias Schmidt, Norichika Kanie	JH and TS developed the idea, JH, TS and NK wrote the paper	Published in <i>Energy Policy</i> 2012, 45 (4), p. 6-11.

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How a Product's Design Hierarchy Shapes the Evolution of Technological Knowledge – Evidence from Patent-Citation Networks in Wind Power [†]

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Abstract

We analyze how a product's design hierarchy shapes the evolution of the underlying body of technological knowledge, building on the literature on technological evolution in complex products. This literature suggests that the design hierarchy of a product can have an ordering effect on the evolution of commercialized artifacts, in particular when product design decisions on high levels of the design hierarchy set the agenda for subsequent variation and experimentation on lower levels. We extend this literature by analyzing the design hierarchy's effect on the evolution of the industry's knowledge base, using the case of wind turbine technology over the period 1973-2009. We assess the technological focus of patents along the core trajectory of knowledge generation, identified through a patent-citation network analysis, and link it to a classification of technological problems into different levels in the design hierarchy. Our analysis suggests that the evolution of an industry's knowledge base along a technological trajectory is not a unidirectional process of gradual refinement: the focus of knowledge generation shifts over time between different sub-systems in a highly sequential pattern, whose order is strongly influenced by the design hierarchy. Each of these shifts initiates a new process of integration of industry-external knowledge into the knowledge base, thus opening windows of competitive opportunity for potential entrants with strong knowledge positions in the sub-system that has moved into the focus of innovation. We discuss implications for the debate on supply-side and demand-side influences along technological trajectories and for the understanding of the competitive advantage of specific knowledge positions of firms and nations.

Keywords: Knowledge dynamics, Technological trajectory, Design hierarchy, Product architecture, Citation-network analysis, Wind power

Abstract

- We develop a methodology to study knowledge evolution along trajectory
- We analyze how focus of patenting in wind turbine technology shifted over time
- We demonstrate that sequence of focus in patenting follows core-periphery pattern
- Each shift in focus initiates new wave of integration of industry-external knowledge
- Our findings can explain shifts in competitive landscape along trajectory

1. Introduction

Complex, systemic products, such as power plants, aircraft and telecommunication networks, are a key entry channel for new technology into the economy (Rosenberg, 1963). Some consider them the ‘frontier’ of the economic development of nations (Hidalgo et al., 2007). They also underpin those sectors – manufacturing, energy, trade and transport – that are at the heart of the world’s environmental challenges. Technological change in such products takes the form of incremental innovation along established technological trajectories (Constant, 1973; Dosi, 1982; Clark, 1985; Frenken, 2006). Understanding the factors that shape the trajectories of technological evolution in complex products is therefore critical for technology strategies as well as economic and environmental policy (Acha et al., 2004; Davies and Hobday, 2005).

A number of qualitative studies emphasize the influence of the hierarchy of design decisions, or design hierarchy, on technological trajectories in complex products (e.g., Hughes, 1983; Clark, 1985; Vincenti, 1990). In particular, evidence suggests that movement along the technological trajectory in complex products is associated with movement down the design hierarchy in two principal ways: First, after a new trajectory has emerged, decisions about the overall product design often ‘set the agenda’ for subsequent change in sub-systems and individual components (Clark, 1985; Murmann and Tushman, 2002; Murmann and Frenken, 2006). Second, changes in sub-systems that perform the core functions of the product tend to precede changes in more peripheral sub-systems (Abernathy and Clark, 1985; Murmann and Frenken, 2006; Lee and Berente, 2013). The movement along the trajectory and down the design hierarchy implies change in the universe of commercialized designs – i.e., the evolution of artifacts – and in the underlying technological understanding – i.e., the evolution of knowledge (Dosi, 1982; Martinelli, 2012). The two are linked but are far from congruent: significant changes in artifacts may be the result of incremental gains of knowledge, and seemingly small changes in artifacts may require large changes in the underlying knowledge base (Funk, 2009; Martinelli, 2012). However, quantitative work on the structuring effect of the design hierarchy on technological trajectories has focused primarily on innovation and the evolution of artifacts (e.g., Saviotti and Trickett, 1992; Frenken et al., 1999; Frenken, 2006; Castaldi et al., 2009; Mendonça, 2012). With few exceptions (Rosenkopf and Nerkar, 1999; Lee and Berente, 2013), the influence of the design hierarchy on invention and the evolution of knowledge have received little attention.

To address this gap, we analyze how a product’s design hierarchy influences the evolution of knowledge. We do so in order to investigate the assumption that the development of an industry’s

knowledge base along the trajectory is predominantly a process of incremental growth and refinement, without cyclical or sequential changes in the focus of inventive activity and the importance of industry-external knowledge. On the one hand, it is commonly assumed that movement down the hierarchy leads to the entrenchment of existing knowledge positions, thus enhancing the competitive advantage of incumbent firms and nations through incremental knowledge growth and refinement, whereas movement up the hierarchy – through the creation of new trajectories – is associated with novel skills and expertise, thus opening windows of opportunity for new entrants (Abernathy and Clark, 1985; Henderson and Clark, 1990; Bekkers and Martinelli, 2012). On the other hand, how the focus of innovation shifts along the technological trajectory has also been at the heart of the more recent debate on the value of supply and demand-side subsidies for stimulating innovation in emerging clean technologies. Because demand-side subsidies are assumed to stimulate movement along existing technological trajectories, recent studies have argued that incentives to deploy technologies such as wind and solar power can be expected to lead to the exploitation and refinement of the existing knowledge base rather than to the exploration of new and potentially more radical solutions (Menanteau, 2000; Nemet, 2009; Hoppmann et al., 2013). A better understanding of how an industry's knowledge base evolves along the trajectory can thus contribute to improved managerial and policy decisions.

In analyzing how a product's design hierarchy influences the evolution of knowledge, this paper links two streams of literature: research on dominant designs and technological evolution in systemic artifacts (e.g., Frenken and Nuvolari, 2004; Murmann and Frenken, 2006; Mendonça, 2012) and research on trajectories of knowledge generation (e.g., Fontana et al., 2009; Barberá-Tomás et al., 2011; Epicoco, 2013). In particular, we develop a novel methodology that combines the manual, categorical analysis of commercialized designs, as employed in studies of dominant designs and technological evolution in systemic artifacts, with patent-citation network analysis, as employed in the literature on knowledge trajectories. This methodology allows us to bridge the artifact and knowledge dimensions by studying the influence of the design hierarchy, which derives from relationships between elements of the physical artifact, on the trajectory of knowledge generation in the industry. We apply this novel methodology to the case of wind turbine technology in the period 1973–2009.

The paper makes several distinct contributions to theory and methodology. Theoretically, we contribute to the literature on knowledge positions and competitive advantage (Bekkers and Martinelli, 2012; Epicoco, 2013; Choi and Anadon, 2014) and the literature on the impact of demand-side subsidies on R&D (Menanteau, 2000; Nemet, 2009; Hoppmann et al., 2013). Our findings suggest

that the evolution of an industry's knowledge base along the technological trajectory is not a unidirectional process of gradual refinement but a sequential process that is structured by the design hierarchy: the focus of knowledge generation shifts over time between different sub-systems, with each shift initiating a new cycle of integration of industry-external knowledge into the knowledge base, a pattern we call creative sequences. Methodologically, our analysis contributes to recent efforts to identify linkages and linking mechanisms between the evolution of knowledge and the evolution of artifacts (Ethiraj, 2007; Barberá-Tomás et al., 2011; Bakker et al., 2012; Martinelli, 2012). We extend the methodology developed by Verspagen (2007) and others to study the knowledge and the artifact dimensions of technological trajectories in an integrated way, which may facilitate a deeper understanding of the interaction between the two domains.

In the following, Section 2 lays out the paper's theoretical perspective and reviews the literature on technological evolution in systemic artifacts. Section 3 introduces the case of wind turbine technology and Section 4 presents the data sources and methodology. The results are presented in Section 5 and discussed in Section 6. Conclusions are summarized in Section 7.

2. Theoretical Perspective

Complex products are conceptualized in this paper as systemic artifacts (Saviotti, 1986; Tushman and Rosenkopf, 1992), consisting of a non-trivial number of interdependent sub-systems and components that jointly enable the system to perform a number of functions, or service characteristics. The sub-systems and components are organized by a product architecture, which allocates system functions to the individual components and defines the interfaces between them (Simon, 1962; Clark, 1985; Baldwin et al., 2014).

Technological evolution in complex products is understood as proceeding predominantly along technological trajectories through refinement within and extension of existing product architectures (Constant, 1973; Dosi, 1982; Frenken, 2006). When referring to sequences in the focus of innovation in the following subsections, we are concerned with incremental innovations along such trajectories.

2.1. The Sequential Pattern of Innovation in Systemic Artifacts

Historians of technology have noted the existence of sequential patterns of innovation in the evolution of technological artifacts (Rosenberg, 1969; Constant, 1980; Hughes, 1983; Vincenti, 1990). In this

context, sequential means that technological progress is concentrated in only a small fraction of a product's components and possible directions of change, and that the focus of this concentration shifts over time between technological problems. The observed sequential pattern also implies that the focus of innovative activity is at least partly collective, in the sense that it can be observed on the level of communities of practitioners rather than individual problem-solvers or firms.

Langes (1969) observed that since the industrial revolution, innovations in technological systems have followed a challenge-response pattern in which technological breakthroughs call forth further, complementary innovations. He described for instance how Kay's flying shuttle (1733), which allowed the development of automatic looms, was followed by rapid development of new spinning devices from the 1750s to the 1770s that supplied yarn more rapidly (Langes, 1969, p. 84).⁷ More generally, several studies have observed that the focus of innovative activity is often on those elements that keep other parts of the system from exploiting their full performance potential, and that new bottlenecks can arise in related components once such performance bottlenecks are resolved (Hughes, 1983, 1992; Sahal, 1985; Ethiraj, 2007; Dedehayir and Mäkinen, 2011). Rosenberg (1969, p. 111) used the term compulsive sequences to describe this self-generating, cyclical nature of problem-solving in systemic artifacts.

2.2. The Influence of the Design Hierarchy on the Evolution of Artifacts

While many had observed the sequential nature of technological change, Clark (1985) first described in detail what determines the sequence of innovative activity among the elements of a systemic artifact. The sequence of innovations in the automotive and semiconductor sectors in their early decades, he argued, can be understood as the outcome of two factors: the hierarchical organization of design decisions on the supply side and the gradual refinement of consumer preferences on the demand side. Murmann and Frenken (2006) integrated these two factors into one model that uses the term design hierarchy to capture the supply and demand side influences on the evolution of systemic artifacts.

⁷ To explain the challenge-response pattern, some economists have invoked induced changes in the relative prices of component technologies or input factors, e.g. the price of yarn in Kay's flying shuttle (Hayami and Ruttan, 1973). Yet, many others have pointed out that as long as the cost of R&D is uncertain, a change in relative factor prices by itself cannot explain the highly selective focus of innovative activity in technological systems (Rosenberg, 1969; Mowery and Rosenberg, 1979; Dosi, 1982).

The design hierarchy locates each element in the system in two hierarchies, which jointly affect the evolution of systemic artifacts (see Figure 1): the hierarchy of nested parts, which locates the element in the hierarchy of systems, sub-systems, components, sub-components, and so on defined by the product architecture; and the hierarchy of control, which orders the elements on each level of the hierarchy of nested parts according to their relative importance for the demanded service characteristics – i.e., the principal categories of variables that underpin consumer choices, such as the speed, cost, noise and visual appearance of a car.

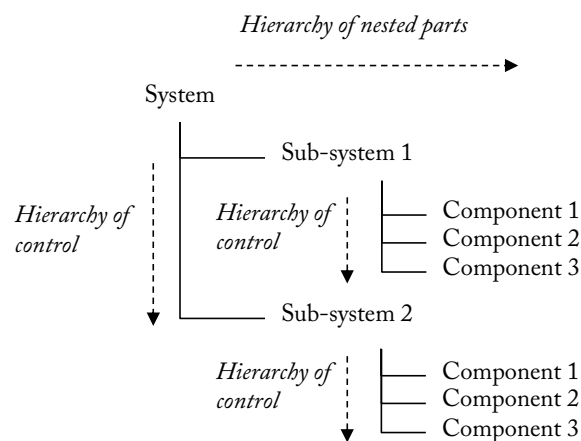


Figure 1: Two dimensions of the design hierarchy of systemic artifacts: the hierarchy of nested parts and the hierarchy of control.

How the hierarchy of control and the hierarchy of nested parts relate to the product architecture and service characteristics is shown in detail in Figure 2. The hierarchy of nested parts reflects the product architecture (arrow a in Figure 2) (Murmann and Tushman, 2002). It captures the tendency of the focus of innovative activity to shift over time from the system-level to sub-systems and components – i.e., from the general to the specific – as certain high-level design decisions set the agenda for incremental problem-solving efforts on lower levels. For instance, design decisions in the combustion chamber component of a piston-driven internal combustion engine have to build on (and thus succeed) system-level design decisions on the type of energy conversion (internal or external combustion) and energy transmission (piston or rotary internal combustion engines).⁸

⁸ In evolutionary theory, this effect is referred to as *downward causation* (Campbell, 1990; Rosenkopf and Nerkar, 1999).

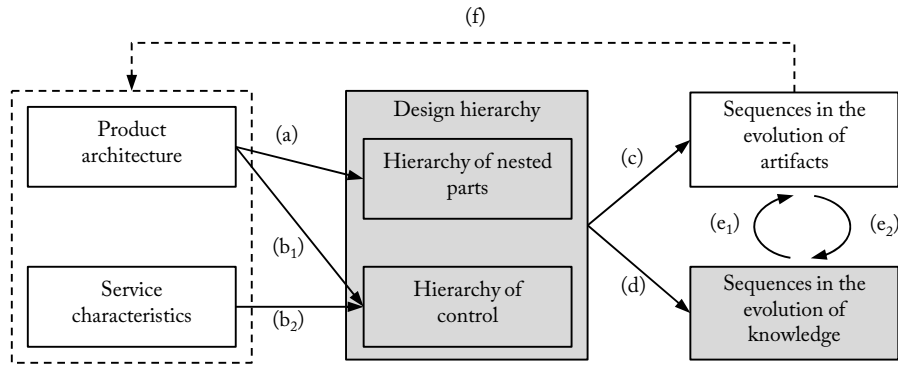


Figure 2: The influence of the design hierarchy on sequences in the evolution of artifacts and the evolution of knowledge (focus of this analysis is marked in grey).

The hierarchy of control reflects the interplay between the product architecture and the service characteristics (arrows b1 and b2 in Figure 2). It captures the effect that even within sub-systems and within components, some design decisions are more important than others and therefore have a controlling influence on them. In particular, when a new trajectory emerges, innovative activity first tends to focus on ‘core’ sub-systems and components that are most relevant to the service characteristics of a product. Later it shifts toward more ‘peripheral’ elements that facilitate the adaptation of certain service characteristics to newly emerging market segments (Lancaster, 1979; Teubal, 1979; Clark, 1985; Saviotti, 1996; Frenken et al., 1999). The focus of innovative activity in the early years of the automobile industry, for example, moved over time from the engine and the steering device to the transmission system, the chassis and other parts of the system (Clark, 1985).

The Murmann-Frenken model predicts that the evolution of artifacts is determined by the joint influence of the hierarchy of control and the hierarchy of nested parts (arrow c in Figure 2).⁹

2.3. The Influence of the Design Hierarchy on the Evolution of Knowledge

Innovation is a process that links the knowledge and artifact dimensions of technological trajectories (arrows e1 and e2 in Figure 2). However, the literature on the influence of the design hierarchy on technological evolution has treated the underlying body of knowledge mostly as a black box. Below we

⁹ Arrow f in Figure 2 is outside the scope of this paper; it captures the effect that in the long-run, incremental innovations along the trajectory can endogenously give rise to new trajectories if innovations and their diffusion in the market alter the demanded service characteristics (Levinthal, 1998) or create opportunities to change the prevailing product architecture (Henderson and Clark, 1990; Funk, 2009).

analyze how the design hierarchy affects the evolution of the knowledge base of an industry – and thus the value of different knowledge positions relative to the core of the trajectory. In particular, we aim to explore whether the Murmann-Frenken model is useful also in conceptualizing how the focus of knowledge generation changes over time as an industry moves along a technological trajectory. In this process, does the trajectory of knowledge move from the general to the specific and from the core to the periphery?

Recent studies provide fragmented evidence that the trajectory of knowledge evolution does reflect the design hierarchy. On a general level, Martinelli (2012) shows that different ‘generations’ of technological artifacts are reflected in the evolution of knowledge trajectories. Within one trajectory, Ethiraj (2007) demonstrates that bottlenecks in the artifact affect the allocation of R&D efforts across the computer industry, and Lee and Berente (2013) use the example of particle filters to show that patenting outside the core component increases once a dominant design for the core component is reached. Lastly, Fontana et al. (2009) briefly mention that the knowledge trajectory of the telecommunication network industry points to an ‘engineering logic’ – which can be interpreted as design hierarchy – governing the sequence of patented inventions, although they do not assess this influence systematically.

However, the evolution of knowledge may differ from the evolution of artifacts in three important respects. First, the body of industry-specific knowledge may exceed what is embodied in commercialized products and services, because firms ‘know more than they make’ (e.g., Brusoni et al., 2001). This means that knowledge generation at any point along the trajectory may not be as focused on specific sub-systems and components as the scope of artifact variation would suggest. Second, firms also make much more than they know, since complex products often employ operating principles that are only imperfectly understood (Vincenti, 1990). Third, not all commercialized knowledge is industry-specific, as firms import a significant share of the knowledge embodied in the artifacts they assemble in the form of components from other sectors (Pavitt, 1984). These last two points mean that some changes on the artifact level may not be reflected in the evolution of the underlying knowledge base. For this reason, processes that depend on the knowledge dimension of technological trajectories, such as knowledge-based competitive advantages of firms and nations (Bekkers and Martinelli, 2012; Epicoco, 2013) or the impact of policy-led incentives on the exploration and exploitation of knowledge (Nemet, 2009; Hoppmann et al., 2013), can only be partially explained using data on the evolution of artifacts. These must be complemented by analyses of the knowledge dimension.

3. Research Case

3.1. Rationale for Case Selection

For empirical studies of the impact of design hierarchy on the evolution of knowledge, the research case should have three specific characteristics.

First, the product needs to be a systemic artifact with a complex product architecture that has multiple levels in the hierarchy of nested parts and several components on each level, which translates into multiple levels in the hierarchy of control. This allows the possible influence of both types of hierarchy. Second, the product should have been produced for as few applications as possible, ideally with relatively stable demanded service characteristics. On one hand, differences in the demanded service characteristics between applications can lead to the bifurcation of artifact trajectories, making the identification of linkages between knowledge and artifact trajectories difficult. On the other hand, changes in the demanded service characteristics over time can induce changes in the design hierarchy and vice versa (see section 2.3). Yet in order to allow for the observation of their structuring effect on the production of knowledge, both the service characteristics and the design hierarchy should ideally remain unchanged throughout the observed period. Third, the majority of progress over the observed time period needs to have taken place along one technological trajectory, because the phenomenon we want to observe by definition only applies to this type of technological change. Over time, innovative activity along the technological trajectory should ideally have focused on different parts of the system, enabling the sequence of shifts in the focus of inventions to be compared to the sequence of shifts in the focus of innovations.

We selected the case of wind turbine technology in the period 1973–2009 because it fulfills all three requirements, and because understanding the evolution of renewable energy technologies such as wind turbines is particularly important to inform public and environmental policy decisions. After an outline of the scope of the analysis in sub-section 3.2, the three requirements are discussed in detail in 3.3–3.5.

3.2. Scope of Analysis

As it is common in research on dominant designs, we use the concept of a shared operational principle to delineate the scope of our research case (Vincenti, 1990; Murmann and Frenken, 2006). We define wind turbine technology as all technologies pertaining to the conversion of wind energy to electricity

by means of a rotor, which is driven by wind and drives an electric generator. This scope includes turbines used for off-grid electricity generation and onshore as well as offshore turbines, but it excludes all wind electricity generators that do not feature a rotor, such as those driven by kites (e.g., as described in patent US 8,319,368). The advantage of applying the shared operational principle to define the scope of analysis is that all included artifacts have a common basic product architecture (Murmann and Frenken, 2006), which allows us to categorize inventions across turbine designs.

3.3. Complex Product Architecture

A typical modern wind turbine consists of a very large number of electrical, mechanical and electronic components which are organized in a complex product architecture, as can be seen in Figure 3 (Section 4.2 describes the derivation of this representation of the product architecture).

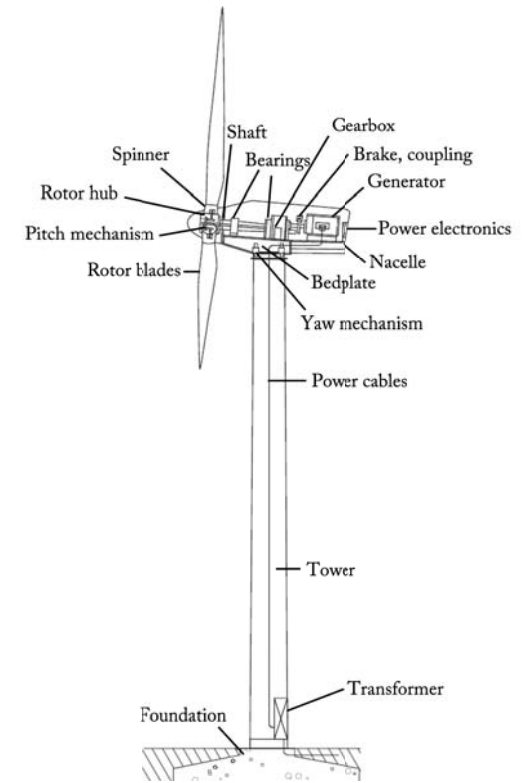
Virtually all wind turbine designs feature a product architecture containing the following four groups of components, which we will refer to as *sub-systems*: (i) a rotor, (ii) a means of converting rotational energy into electrical energy (the power train), (iii) some form of mounting and machine encapsulation (typically the foundation, the tower and the nacelle), and (iv) some form of grid-connection (or electricity storage unit in the case of off-grid generation).¹⁰ This common product architecture has multiple levels of nested parts: each of the four main sub-systems contains components, which are made up of sub-components, and so on. The power train (sub-system ii), for example, contains the mechanical drive-train, which contains a gearbox. The gearbox, in turn, consists of cogwheels, shafts, a lubrication system, which are all again made up of various smaller parts. The fact that the product architecture features four sub-systems and three to four components for each sub-system means that the hierarchy of control has multiple levels, too.

¹⁰ As an illustration of the complexity of design choices within this common product architecture, Table A1 in the appendix summarizes the main engineering tasks involved in wind turbine design (including the main underlying knowledge domains), and Table A2 illustrates the scope of design decisions for each sub-system and most of the components.

**Table 1: Product architecture of a typical wind turbine used for grid-connected electricity generation:
Sub-systems and components and their functions in the technological system.**

Sub-systems and components	Function
Wind turbine (system-level)	Conversion of wind energy into grid electricity
Rotor	
Blades	Conversion of wind energy into rotational energy
Hub	Transfer of rotational energy to main shaft
Rotor control system (pitch and yaw mechanisms), control routines	Adjustment of rotor and individual blades to wind conditions
Power train	
Mechanical drive-train: Rotor shaft, bearings, gearbox, couplings, brake	Transmission of rotational energy from rotor blades to generator
Electrical drive-train: generator, power electronics	Conversion of rotational energy into electrical energy; AC-DC and frequency conversion
Power-train control system and routines	Adjustment of drive-train elements to wind & system conditions
Mounting & encapsulation	
Nacelle, spinner and bedplate	Load carrying; machinery enclosure
Tower	Support turbine at designated height; load transfer to foundation
Foundation	Load transfer into ground
Climate & vibration control system and routines	Regulate operating conditions & minimize system vibrations
Grid connection and/or storage	
Transformer / substation and power cables	Transfer of electrical energy to grid
Storage (if applicable)	Storage of electrical energy
Grid-impact and wind-farm control system and routines	Reduce impact of grid-side disturbances; ensure grid-friendly wind farm output

Figure 3: Components of a wind turbine (adapted from Hau, 2013).



3.4. Stable Service Characteristics

Wind turbines have been produced almost exclusively for onshore, grid-connected electricity generation. Of the roughly 198 gigawatt (GW) installed globally by the end of 2010, only 0.4 GW are small wind turbines (<100 KW), which represent most of the off-grid market (WWEA, 2012), and about 3 GW are installed offshore (GWEC, 2011). This dominance of the onshore, grid-connected market over other segments has prevailed throughout 1973-2009. Therefore, the demanded service characteristics can be approximated as relatively stable in the observed period.

A further benefit for our study arises from the fact that virtually all markets for wind turbines around the globe are created through public policy support. Because the demanded service characteristics are legislated ex-ante, rather than gradually developed by consumers, we can consider them as exogenous to the evolution of artifacts and knowledge. This minimizes the risk of potential endogeneity stemming from the long-term effects of technological change on consumer demand (arrow f in Figure 2).

3.5. Technological Change along one Trajectory

Technological change in wind turbine technology over the last three to four decades has been predominantly characterized by incremental innovations along the trajectory of scaling-up and refining one overarching system design: a horizontal-axis rotor with airfoil-shaped blades that utilize the lift forces of the wind.

Figure 4a shows how the price of wind turbines per watt of electric capacity has come down gradually as the technology progressed along the trajectory. The incremental nature of technological change is also visible in Figure 4b, which shows how the average rotor diameter, turbine capacity and hub height have all increased gradually since 1980.

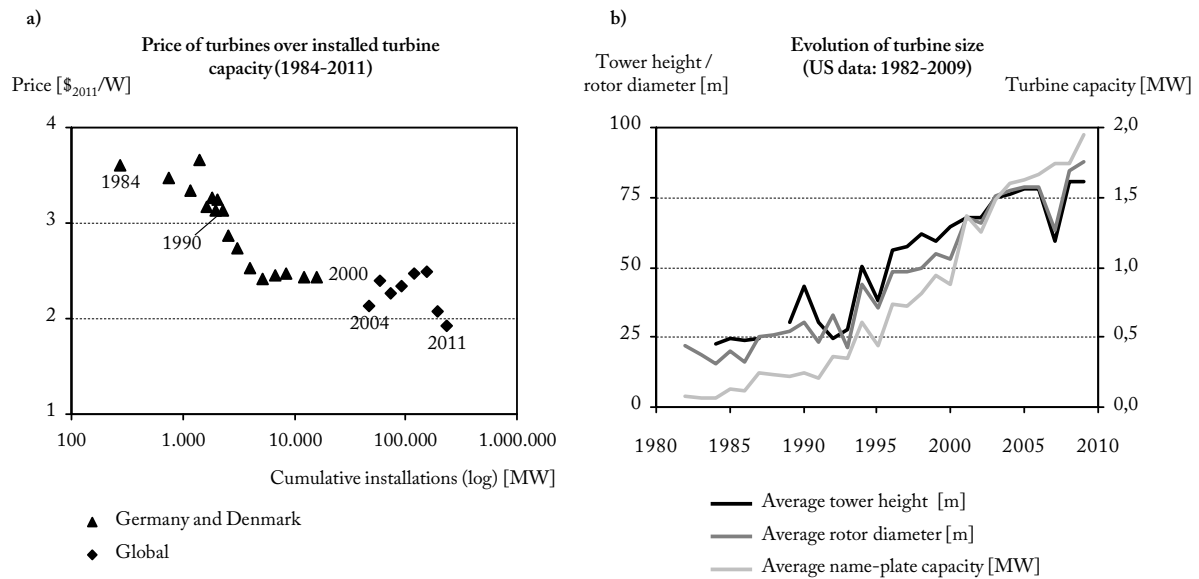


Figure 4: a) Price development of wind turbines over cumulative installations; data from BNEF (2012). b) Size trajectories of modern wind turbines: rotor, name-plate capacity and tower height; data from USGS (2014).

Data on design competition suggests that the focus of innovative activity has shifted over time as the technology has moved along the trajectory (Figure 5a and b). In the late 1970s and early 1980s, firms experimented with different positions of the rotor relative to the tower (upwind, downwind), blade numbers (one, two, three, four or more blades were all introduced commercially) and rotor control mechanisms. As Figure 5a shows, it was not before 1986 that more than 50% of the firms in the market had adopted the three-blade, upwind rotor called the 'Danish design,' which is now used in virtually all grid-connected wind turbines.

The focus of innovative activity then shifted within the Danish rotor design toward more efficient power train concepts, as can be seen from the adoption of variable-speed power trains starting from the early 1990s (in white in Figure 5a). The most intense period of design competition on the power-train level was in the late 1990s and early 2000s, when the variable-speed power train with a partial-scale converter emerged as dominant design. It has held more than 50% market share since around 2003.

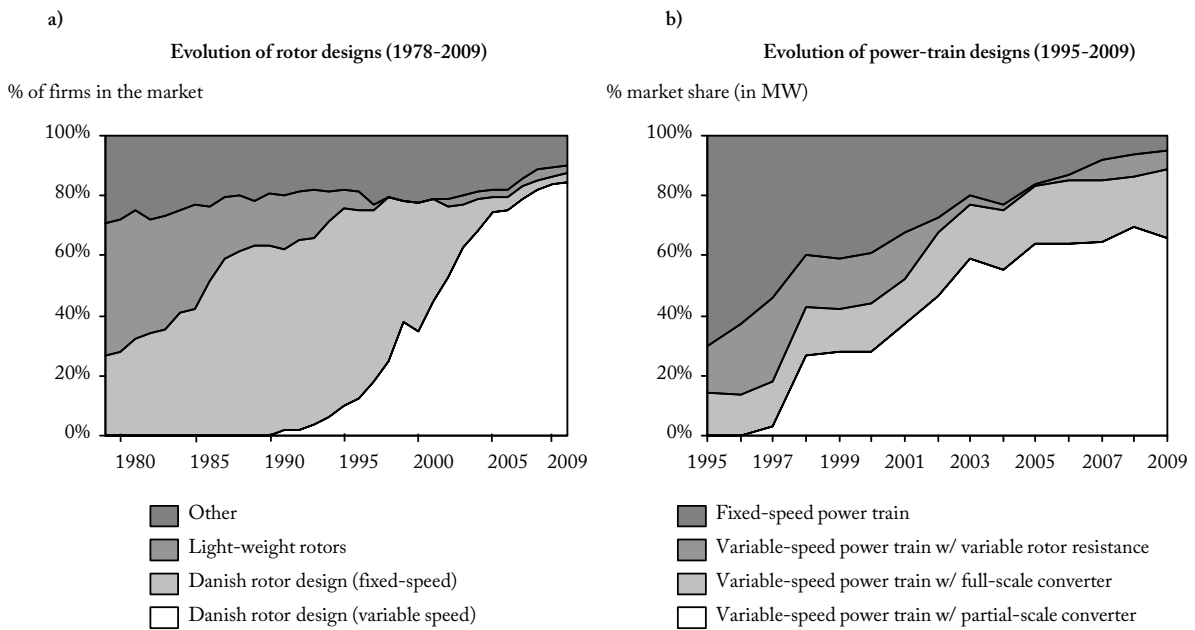


Figure 5: Evolution of wind turbine designs: a) the number of firms with different rotor designs in 1978-2009; data from Menzel and Kammer (2011). b) Market share of different power-train designs in 1995-2009; data from Hansen (2012).

What cannot be analyzed with data on artifact evolution such as those presented in Figure 5 are trends in the underlying knowledge base. One can only speculate, for example, whether the surge in variable speed turbines in the 1990s was based on industry-internal refinement in the understanding of wind-specific drive-train requirements or was based on ‘imported’ advances in standardized drive-train components used in other industries. However, these trends directly affect the competitive position of firms and nations, and they have implications for the assessment of innovation policies in the wind industry. Below we proceed to open this black box.

4. Data and Methodology

4.1. Empirical Strategy

In this section, we develop a systematic approach to determining the impact of the design hierarchy on the trajectory of knowledge generation in complex products.

Recent studies of the knowledge dimension of technological trajectories have made significant advances by applying citation-network analysis to patent data (Verspagen, 2007; Fontana et al., 2009; Barberá-Tomás et al., 2011; Martinelli, 2012; Epicoco, 2013). This approach allows researchers to trace the trajectory of knowledge generation over time, but it cannot easily link it to the evolution of

artifacts and dominant designs (Barberá-Tomás et al., 2011). Studies of the artifact dimension of technological trajectories, on the other hand, have traditionally relied on categorical analysis of product designs available in the market (Rosenkopf and Nerkar, 1999; Frenken and Nuvolari, 2004; Fixson and Park, 2008; Mendonça, 2012). This approach is useful for analyzing the influence of the design hierarchy on the evolution of artifacts but does not allow identification of developments in the underlying knowledge base. Combining these two approaches allows us to identify the influence of the design hierarchy on the trajectory of knowledge generation and thus to bridge the knowledge and artifact dimensions of technological trajectories.

Our empirical strategy was as follows: We first used a combination of desk research and expert interviews to identify the product architecture, relevant service characteristics and design hierarchy of wind turbines (Section 4.2). Second, we analyzed connectivity measures in the network formed by wind turbine patents and patent citations in order to identify the core trajectory of knowledge generation (the data is described in Section 4.3 and the algorithms in 4.4). In particular, we analyzed how the core trajectory of knowledge generation *evolved* and *converged* over time, by investigating how the core of the knowledge trajectory changes as an ever-increasing number of patents add to the knowledge base over time. We then analyzed in detail the core trajectory of the complete knowledge base, which we will refer to as 'today's core trajectory,' to determine how the focus of inventive activity along the trajectory shifted over the course of the last four decades. In a third and final step, we manually categorized the core patents on the trajectory of knowledge generation, identified in step two, according to their focus in the design hierarchy (Section 4.5). Taken together, these three steps yield a unique database of key inventions along the trajectory of knowledge generation that allows us to trace how the trajectory gradually proceeds through the wind turbines' design hierarchy.

4.2. Design Hierarchy

The design hierarchy was identified through a qualitative assessment of the product architecture, the relevant service characteristics, and the linkages between the two.

We first developed an initial understanding of the product architecture from the technical literature. Then this initial understanding was iteratively refined through five semi-structured telephone interviews with two industry professionals. The resulting product architecture is shown in Figure 6.

The list of relevant service characteristics was identified through a series of nine structured interviews,¹¹ in which we asked for characteristics that determine model choice. From the resulting long list of criteria we removed turbine model-specific characteristics such as the availability of upgrades and spare parts as well as purely organizational characteristics such as warranty time, contract flexibility, reaction time, etc. We further aggregated some criteria to reduce complexity. (The final selection is shown in the column headers of Table A4 in the Appendix.)

Lastly, the design hierarchy, which is determined by the linkages between the product architecture and the service characteristics, was developed through structured interviews with two industry professionals, in which we asked them to link sub-systems and components of a wind turbine to the identified list of service characteristics. We contacted the interviewees a second time to clarify inconsistencies between the two and removed linkages where disagreement could not be resolved.

4.3. Patent and Patent Citation Data

We used patents as indicators of knowledge generation in the wind industry (Nemet, 2009) and citations as indicators of technological relatedness (von Wartburg et al., 2005).

For the underlying patent database, we compiled wind patents¹² filed from 1963 to 2009 from the Derwent World Patent Index (DWPI) database, which contains patents from 48 patent-issuing authorities worldwide.¹³ We chose DWPI because it facilitated the assessment of patent content by providing expert-generated abstracts of all patents (see Section 4.5), including translated abstracts for non-English entries in the database. The search was conducted in early 2013 in order to account for the time-lag between patent filing and publication of patents filed in 2009.

The patent database was compiled by applying a list of keywords to the titles, abstracts and claims of patents in 20 four-digit International Patent Classification (IPC) classes. We extracted an initial list

¹¹ For this step we interviewed professionals (by telephone and on-site) from two wind turbine operators and wind turbine experts from one insurance company, one engineering service provider, one bank, one consultant and one project developer.

¹² We used patent families as the unit of analysis to avoid double-counting of multiple filings.

¹³ Even though our focus is on the time period 1973–2009, the database includes patents from 1963–1972 in order to improve the results of the connectivity analysis for the earliest patents.

of relevant keywords from the technical literature (four industry experts provided feedback on the identified keywords) and an initial set of wind-related IPC classes from the 'Green Inventory' of the World Intellectual Property Organization. We then iteratively curtailed the keyword list and IPC classes by manually checking random samples of patents for irrelevant keywords, and we added further IPC classes by analyzing in which IPC classes relevant patents in the database were co-filed. The combination of keywords and IPC classes yielded a total of 25,512 patent families (including applications and granted patents). After retrieving the citation data of all patents, we extended the database in a second iteration to include those 1,000 outside patents that received the most citations from the patents in the database (almost all of these are wind patents). Tests indicate the presence of about 6% false positives and 9% false negatives in the final dataset.¹⁴

The citation data was extracted from the DWPI and in addition from the Thompson Innovation database. Neither of the two databases alone provides citation data for the full period from all patent offices that we deemed important for the case of wind power, but taken together the coverage is satisfying.¹⁵ We cleaned the citations of duplicates and excluded all patents that were not connected to other patents in the network. Finally, we reversed the citations to transform them into indicators of knowledge inheritance between nodes in the network, and we excluded circular references¹⁶ (Martinelli and Nomaler, 2014). The final database contains 11,330 patent families with 41,268 citations between them (network A in Table 2).

¹⁴ To test for false positives, we randomly tested a total of 1,000 patents (50 patents for each of the 20 four-digit IPC classes in the search string). For false negatives, we checked how many of the patents filed by the top 8 pure-player wind turbine manufacturers (in 2010 by market share) were included in our database.

¹⁵ We considered as important the 12 countries with the most successful turbine manufacturers (by market share) in the observed period as well as the multilateral patent offices (in country codes of the World Intellectual Property Organization): BE, CN, DK, DE, ES, EP, GB, IN, IT, JP, KR, NL, US, WO. Gaps that remained even after combining citation data from both databases are: BE before 1987, CN, ES before 1992, IN, IT before 1986, KR before 2008.

¹⁶ Whenever we found circular references, i.e., mutual citations between patents, we deleted the citation coming from the patent with the earlier priority date. Such citations can occur when examiners add citations to new patents filed during the examination process, or when patents are filed in multiple countries.

4.4. Patent-Citation Network Analysis

Connectivity analysis of networks created from patents (as vertices) and patent citations (as arcs) has emerged as a standard approach for analyzing the knowledge dimension of technological trajectories (Mina et al., 2007; Fontana et al., 2009; Barberá-Tomás et al., 2011; Bekkers and Martinelli, 2012; Martinelli, 2012; Epicoco et al., 2014). We employed connectivity analysis with two objectives: to investigate how the core trajectory of knowledge production *evolved* over time, and to analyze the *foundations of today's core trajectory* in detail to determine how the focus of inventive activity along this trajectory shifted over the course of the last four decades. For both objectives, we used connectivity algorithms to extract sub-networks that could then be categorized manually (see Section 4.5).

To address the first objective, we extracted a series of gradually growing sub-networks that allowed us to analyze how the core trajectory of knowledge generation in the wind industry varied and converged over time. This approach reflects the fact that the core trajectory of knowledge generation identified in an industry's knowledge base at any point in time, represented here by a set of patents, changes *ex-post* when new knowledge is added over time: the (patented) roots of what the industry is working on today may have been *outside* the industry's focus of knowledge generation at the time they were filed, and patents *inside* the focus in the 1980s may have become obsolete by now.

We began by specifying a series of gradually growing networks N_t , in which each N_t contains all patents filed between 1963 and the year $t=1975\dots 2009$ and the citations between them (network set B in Table 2).¹⁷ We only included citations with a lag between the application dates of the citing and cited patents of no more than five years so as not to disproportionately weigh older patents that had more time to get cited. For each N_t we applied the search path link count (SPLC) algorithm (Hummon and Doreian, 1989; Verspagen, 2007). This allowed us to determine vertex and arc weights, which represent the importance of patents and citation linkages for the cumulative evolution of technological knowledge represented by the network, and act as input to the connectivity algorithms described below.

¹⁷ The year 1975 was chosen as a starting point because at that time the cumulative number of patents exceeded 100.

We then used the critical path method to identify the ‘backbone’ of each network N_t , which can be understood as a core trajectory of knowledge generation in the observed period (Mina et al., 2007; Fontana et al., 2009; Barberá-Tomás et al., 2011; Bekkers and Martinelli, 2012; Martinelli, 2012; Epicoco et al., 2014). Thereafter, we extracted each resulting critical path as a separate sub-network – one for each N_t (network set C in Table 2) – and categorized all contained patents according to their content (see Section 4.5). By displaying the sub-networks individually and identifying change and stability over time, we were able to observe how the core trajectory of knowledge evolution varied and converged over time.

To address the second objective, investigating in detail the focus of inventive activity along today's core trajectory over the last four decades, we started with the full network (1963-2009) and again used the SPLC algorithm to weigh vertices and arcs. Instead of using the critical path method, however, we extracted the two sub-networks containing 80% and 95% of the total vertex weight, respectively (networks D and E in Table 2). Because the weight of patents in the network is highly skewed, with a few patents holding most of the aggregate weight, this vertex-cut algorithm (Batagelj and Mrvar, 2004) reduces the number of patents in the network significantly – in our case from 8,907 to 494 for 95% of the aggregate vertex weight and 158 for 80% (see Table 2). This allows us to approximate characteristics of the full network, such as the focus of inventive activity in the design hierarchy, by categorizing only a relatively small subsample. In particular, we can obtain a close approximation of the weighted average of the focus of inventive activity in the full network of 8,907 patents by manually categorizing only 494 patents.

Table 2: Descriptive statistics of (sub-) networks and their role in the analysis.

(Sets of) Networks	Content	Number of networks	Time period	Patents (citation links)	Manually coded (y/n)	Analysis steps
A	All patents	1	1963-2009	11,330 (41,268)	No	---
B	Sequential full networks, citation links ≤ 5 years	35	1963-1975 ... 1963-2009 (in year-steps)	111 (43) ... 8,907 (18,718)	No	Calculation of vertex and arc weights to determine critical paths (see set C)
C	Sequential critical paths	35	1963-1975 ... 1963-2009 (in year-steps)	4 (3) ... 33 (32)	Yes	Variation of core trajectory over time (Figure 7)
D	Patents with top 80% of vertex weight	1	1963-2009	158 (499)	Yes	Analysis of focus of inventive activity along today's core trajectory (Figure 8)
E	Patents with top 95% vertex weight	1	1963-2009	494 (1,827)	Yes	Robustness check for analysis of dominant knowledge trajectory
F	Patents with top 80% vertex weight (all citations)	1	1963-2009	158 (817)	Yes	Analysis of knowledge flows between patents on today's core trajectory (Figure 8)

4.5. Patent-Content Analysis

As a final step, we manually coded the abstracts and claims of the patents in the sub-networks extracted in Section 4.4 to identify how the industry's knowledge base evolved over time (networks C-F in Table 2). One mechanical engineer and one electrical engineer independently coded each of the patents according to the abstracts' focus and located them in the design hierarchy.

The coding scheme we used in the analysis, shown in Table 2, has three levels in the hierarchy of nested parts (system, sub-system and component) and four levels in the hierarchy of control on the sub-system level (rotor, power train, mounting & encapsulation and grid connection).¹⁸ The

¹⁸ The initial coding scheme also had a sub-component level. However, the agreement between the two coders was not high enough to justify a distinction between the component and sub-component level (<70%), and in all but one component the agreement between the two coders on the distinction between different sub-components (such as between generators and power electronics) was also insufficient (<80%).

agreement between the two coders was 89% in the hierarchy of nested parts and 92% in the hierarchy of control.

We cross-checked the resulting focuses of knowledge generation along the trajectory in a final round of interviews with four academic experts on the wind industry. All four confirmed the trends displayed in the data.

Table 3: Coding scheme for patent focus.

Content code	Content	Example
Wind turbine (system-level)	Novel wind-turbine design in which novelty has to do with the design of at least two sub-systems (rotor, power train, mounting & encapsulation, and/or grid connection)	Vertical axis turbine with novel rotor and novel drive-train arrangement (US 3,902,072) or horizontal-axis rotor with rotor-integrated generator (US 4,289,970)
Rotor (sub-system level)	Novel rotor design in which novelty has to do with the design of at least two components (blades, hub and/or rotor control)	Rotor arrangement with teetering hub and rotor control mechanism (US 4,201,514)
Rotor (component level)	Novel rotor design in which novelty has to do with the design of one component (blades, hub and/or rotor control)	Sectioned rotor blade (US 4,389,162)
Power train (sub-system)	Novel power-train design in which novelty has to do with the design of at least two components (mechanical transmission system, generator, power electronics, power-train control)	Compact, gearless power train (US 6,921,243)
Power train (component)	Novel power train design in which novelty has to do with the design of one component (mechanical transmission system, generator, power electronics, power-train control)C	Planetary gearbox (US 6,420,808)
Mounting & encapsulation (sub-system)	Novel mounting & encapsulation design n which novelty has to do with the design of at least two components (nacelle, spinner, bedplate, tower, foundation, climate & system-vibration control)	Novel tower-nacelle arrangement in which transformer is mounted inside the top of the tower (US 7,119,453)
Mounting & encapsulation (component)	Novel mounting & encapsulation design in which novelty has to do with the design of one component (nacelle, spinner, bedplate, tower, foundation, climate & system-vibration control)	Tower consisting of pre-fabricated modules (US 7,770,343)
Grid connection (sub-system)	Novel grid-connection design in which novelty has to do with the design of at least two components (mechanical transmission system, generator, power electronics)	Novel electrical connection of wind turbines in a wind farm, including substation and individual transformers and cabling (US 7,071,579)
Grid connection (component)	Novel power train design in which novelty has to do with the design of one component (transformer, substation, cabling, storage, wind-farm integration control, grid-fault control)	Control system for wind farm that optimizes voltage and reactive power output (US 7,119,452)

We were further able to test the robustness of the coding by assessing whether or not the categorization of sub-systems is reflected in the citation data, because previous research has shown that patent citations are more likely to link patents within than across sub-systems and components (Rosenkopf and Nerkar, 1999). χ^2 tests for the randomness of the distribution of citations from each

of the four sub-systems indicate that the results of the coding do indeed correspond to relational patterns in the citation data (see Table A3).

5. Results

5.1. Design Hierarchy

The design hierarchy, displayed in Figure 6, is derived from the interplay of the product architecture and the service characteristics. The product architecture directly yields the hierarchy of nested parts, with the turbine system on the system-level, the rotor, power train, mounting & encapsulation and grid connection on the sub-system level, and all other elements on the component level.

The hierarchy of control is determined on the sub-system level by assessing the influence of each sub-system on the service characteristics. Specifically, each sub-system's position in the hierarchy of control is calculated from the number of service characteristics affected by the sub-system. The underlying relationships between system elements and service characteristics are presented in Table A4 in the Appendix (Murmman and Frenken, 2006). Our results suggest that the hierarchy of control of a wind turbine follows the order (from core to periphery) (i) rotor, (ii) power train, (iii) mounting & encapsulation and (iv) grid connection, as indicated by the vertical order of the sub-systems in Figure 6.¹⁹

¹⁹ The resulting design hierarchy is in line with the prominent role that rotor and power-train designs assume in historical accounts of wind turbine engineering (Karnøe, 1993; Gipe, 1995; Garrad, 2012).

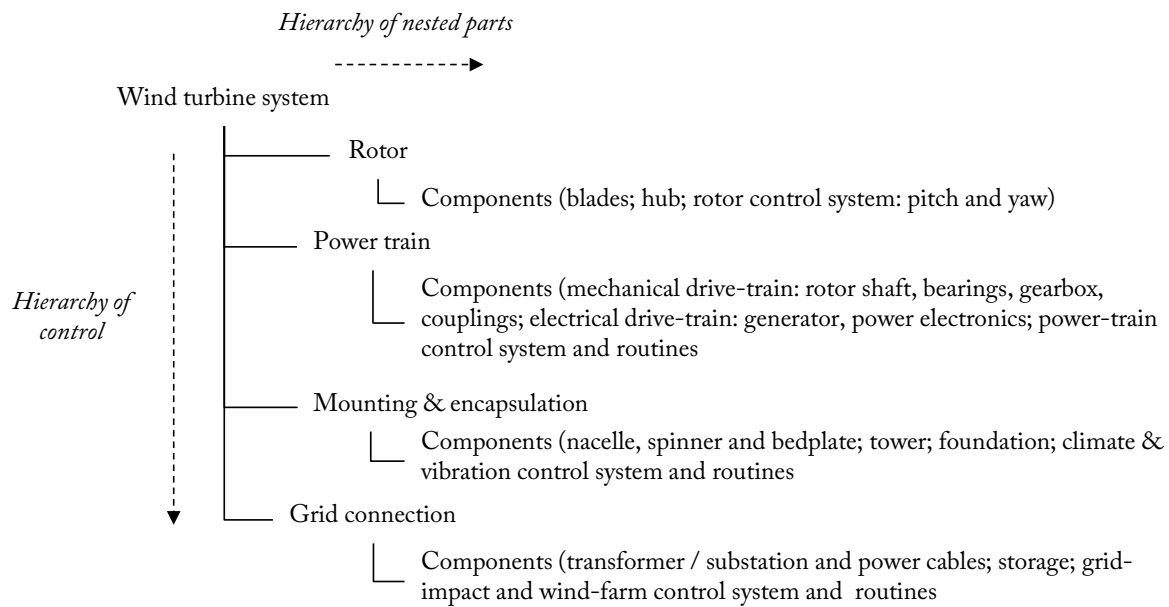


Figure 6: Design hierarchy of a wind turbine, based on product architecture presented in Table 1 and pleiotropy map presented in Table A4 in the appendix.

5.2. Gradual Stabilization of Knowledge Trajectory

The evolution of the core trajectory over the last four decades was analyzed iteratively by determining the core trajectory as increasingly more years of data are added to the patent-citation network. Figures 7a-h shows how the core trajectory meanders through the design hierarchy for eight networks representing network growth in 5-year steps. It can be seen how the knowledge trajectory in the industry varies substantially from 1974, the year when the earliest core trajectory begins, until 1990, but stabilizes thereafter. This result is quantified in Figure 7i, which displays for each year t the percentage of the patents on the core trajectory of network N_t (i.e., the network with data until year t) that are no longer on the core trajectory of N_{t+5} . Only by 1990 does this hazard rate, which is a measure of variation of the core trajectory, remain consistently below 50% (the value in 1989 is exactly 50%). Accordingly, our analysis is able to describe the competition between fundamentally different engineering approaches in the 1970s and 1980s as well as the subsequent convergence on the ‘Danish’ bottom-up approach to wind turbine design. This convergence had been described extensively, but only in qualitative studies (e.g., Karnøe, 1993b; Gipe, 1995; Johnson and Jacobsson, 2000; Garud and Karnøe, 2003; Nielsen, 2010). The sequence of core paths in Figure 7 indicates that the knowledge trajectory stabilized as soon as the core patents on the rotor stabilized: while there is much variation between the rotor-level patents in the networks N_{1975} – N_{1990} , there is no further change on the rotor level from N_{1995} on, which coincides with the stabilization of the knowledge trajectory overall. This

suggests that the dominant rotor design reduced variation on the highest level in the hierarchy of control, but set the agenda for further developments and thus allowed for much innovation on lower levels of the design hierarchy (cf. Clark, 1985; Sahal, 1985; Frenken, 2006; Murmann and Frenken, 2006).²⁰

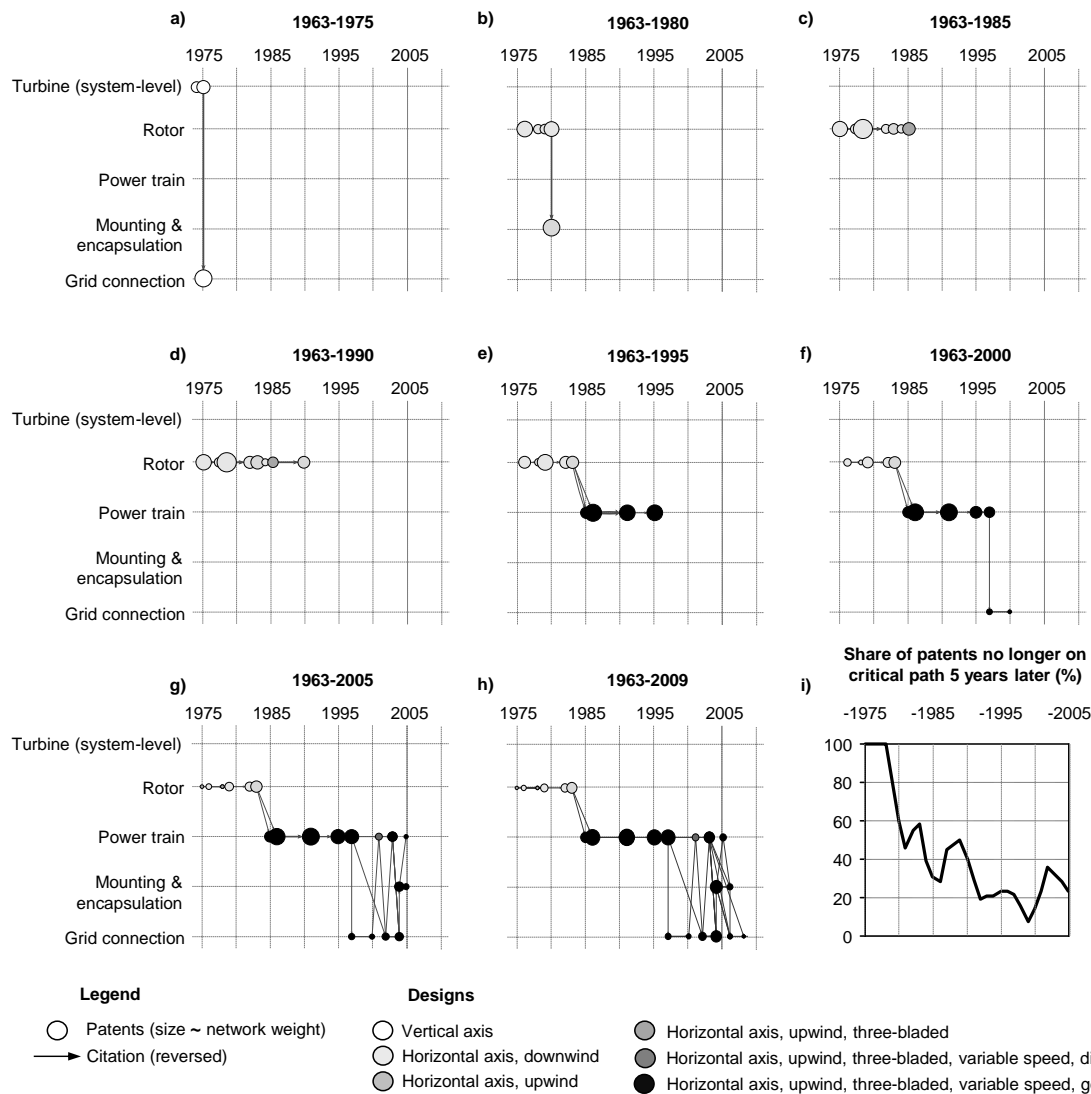


Figure 7: Variation of core trajectory over time. a)-h) display the critical paths in a series of gradually growing networks (time periods are given in parentheses). Figure i) shows the five-year hazard rate for patents on the core path, indicating how the core trajectory gradually stabilizes over time. The size of vertices and arcs represents their weight. The shade of the vertices indicates the rotor and power-train design underlying the invention; patents without any specific rotor and/or power-train design are colored as black.

²⁰ Table A5 in the appendix provides details on content and assignees of the patents along the top path of the core trajectory.

5.3. Foundations of Today's Trajectory of Knowledge Generation

The analysis of the networks with patents that represent 80% and 95% of the vertex weight in the network confirms the overall trend shown in Figure 7h, while adding further depth and detail. Figure 8 shows the network of those patents that account for 80% of the vertex weight. Significant inventions along the trajectory can be found in all four sub-systems and across all levels of the hierarchy of nested parts, underlining the complex, systemic character of wind turbines. However, the focus of inventive activity shifted through the system in a clearly *sequential* way: from the rotor to the power train, grid connection and lastly mounting & encapsulation.²¹

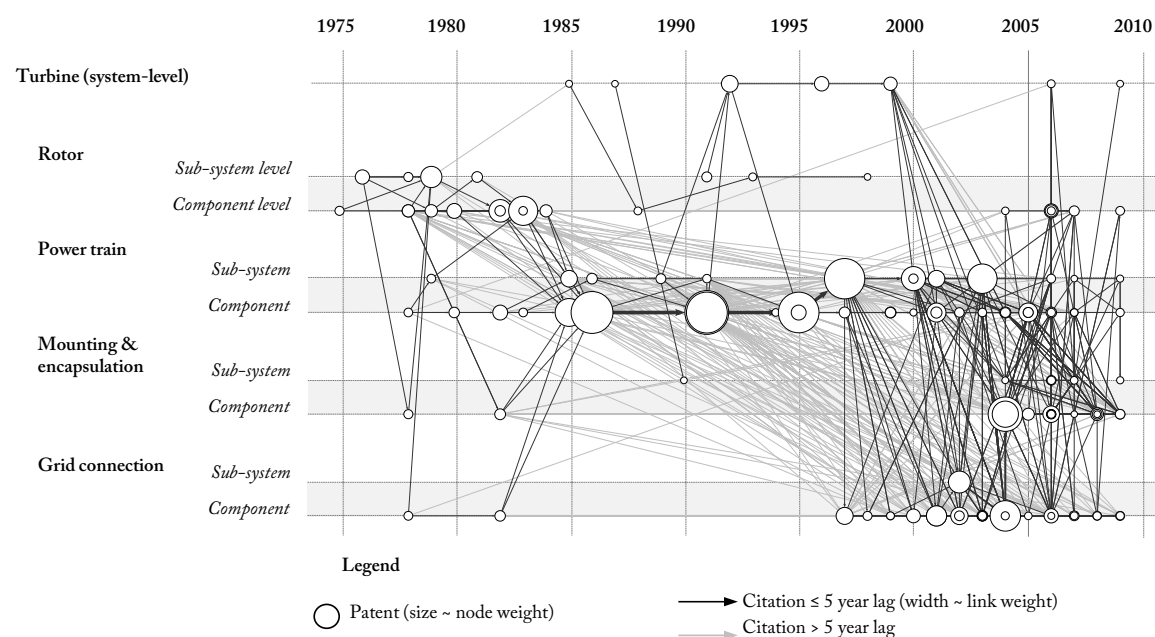


Figure 8: History and foundations of today's trajectory of knowledge evolution in the wind industry in detail (represented here by the network containing 80% of the total vertex weight). Citations with lag >5 years were not used in analysis, but are displayed here to indicate actual technological linkages.

An analysis of the 95%-weight network, shown in Figure 9, provides further quantitative evidence for (i) the highly sequential pattern of knowledge generation along the trajectory, and (ii) the structuring effect of the hierarchy of control on the underlying sequence. Expressed in terms of the hierarchy of nested parts, across the observed period, most inventive activity is on the component level (Figure 9a),

²¹ Notably, the full sequence through all sub-systems took more than 30 years (from 1975 to around 2005, when the last sub-system was reached), highlighting the complex, systemic nature of wind turbines.

while there is no clear trend in the inventions on the system- and sub-system levels. In contrast, the hierarchy of control is well reflected in the sequence of inventive activity along the trajectory (see Figure 9b and Table A6 in the Appendix): Rotor patents account for 77% of the total vertex weight in 1975-1979 and for 76% in 1980-1984, but only for an average of 3% in the two subsequent decades. Power train patents, on the other hand, surge from 16% in 1980-1984 to 91%, 87% and 78% in the three periods after that, before falling to 34% in 2000-2004. The last two periods are dominated by grid connection patents, with 46% in 2000-2004, and mounting & encapsulation with 32% in 2005-2009, two categories that both had 0 patents in the 95%-weight network in 1985-1989.²² Toward the end of the observed period, the focus of knowledge generation seems to diffuse.²³

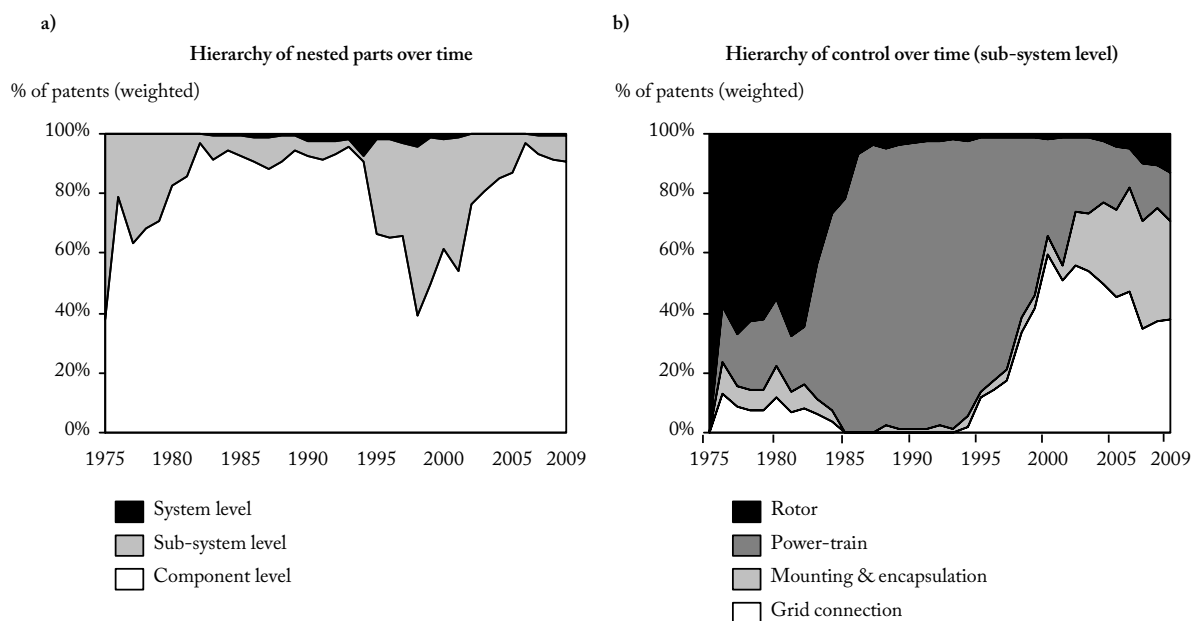


Figure 9: Weighted-average of the focus of patents over time: (a) hierarchy of nested parts and (b) hierarchy of control; data from patents representing 95% of vertex weight in the network (determined through a search path link count algorithm). Data displayed as 5-year moving averages.

The presented results suggest that the design hierarchy had a structuring effect on the trajectory of knowledge evolution in the wind industry, albeit with two qualifications. First, although the earliest

²² An ordered, bivariate ordinal regression of the hierarchy of control on the logarithmized cumulative number of patents in the network confirms that inventive activity gradually shifts downwards on the hierarchy as the knowledge base grows ($\beta=0.60$; $t(494)=6.53$; $p<0.001$, $AIC=1437$).

²³ This observation might be partly due to the fact that patents had lower chances of being cited in the last four years.

patents in the field of mounting & encapsulation precede those in grid connections, significant activity in the latter field occurred earlier (after 1995). This coincides with the first regulations on grid-compatibility in the industry in the late 1990s, which suggests that the early shift was due to the temporarily heightened urgency of a single service characteristic (grid compatibility; discussed further in section 6.4). Second, the hierarchy of nested parts appears not to be a good predictor of the sequence of knowledge generation along today's knowledge trajectory. On one hand, inventive activity did not start on the system level (at least not in patents filed from 1963).²⁴ On the other, in all four subsystems the earliest inventive activity is on the component level, rather than on the sub-system level. And in all sub-systems but the rotor, which features significant patents on the sub-system level early on, the vertices on the component level appear much more important than those one level higher. One possible explanation for this second qualification is that inventors had network-external knowledge on the system-level and sub-system level to build on, for example in the form of standardized generators, towers and transformers available in other industries, and thus could focus immediately on wind-specific improvements on the component-level. To shed more light on this possible explanation, we analyzed below the relative importance of network-external knowledge over time.

5.4. Influence of Network-External Knowledge along Trajectory

Figure 10 plots the influence of external knowledge, measured by the weighted-average share of citations to patents outside the network. As can be seen in Figure 10a, which shows the relationship for the full 95%-weight network, the influx of industry-external knowledge consistently declines over time. However, as indicated by Figure 10b, which shows the relationship for each sub-system separately, this decline is not uniform across the elements of the system; rather, each sub-system features very different rates of decline.

The data is plotted *over the cumulative vertex weight*, rather than over time, to show that the decrease is primarily a function of how much knowledge has been generated *within the specific sub-system*,

²⁴ However, system-level inventions did have some impact later. The patents on the system-level in the late 1990s as well as the recipient patents on lower levels relate to direct-drive technology, a specific type of power train that does not need a gearbox.

rather than along the trajectory in general. This means that external knowledge gained importance whenever the focus of inventive activity shifted to a new sub-system.

The high intercept of the rotor function indicates that very little network-internal knowledge was available to build upon, but the relatively steep slope suggests that it was built up as a largely independent knowledge base. In contrast, the lower intercept of the power-train, mounting & encapsulation, and grid-connection functions reflects their being in focus in later stages of the trajectory: inventions in these sub-systems could partially build on a wind-specific knowledge base that had already been developed. However, their more moderate slope also indicates that there was more persistent import of external knowledge. This reflects the fact that, unlike rotor blades, these sub-systems and components have much in common with other electro-mechanical machinery.

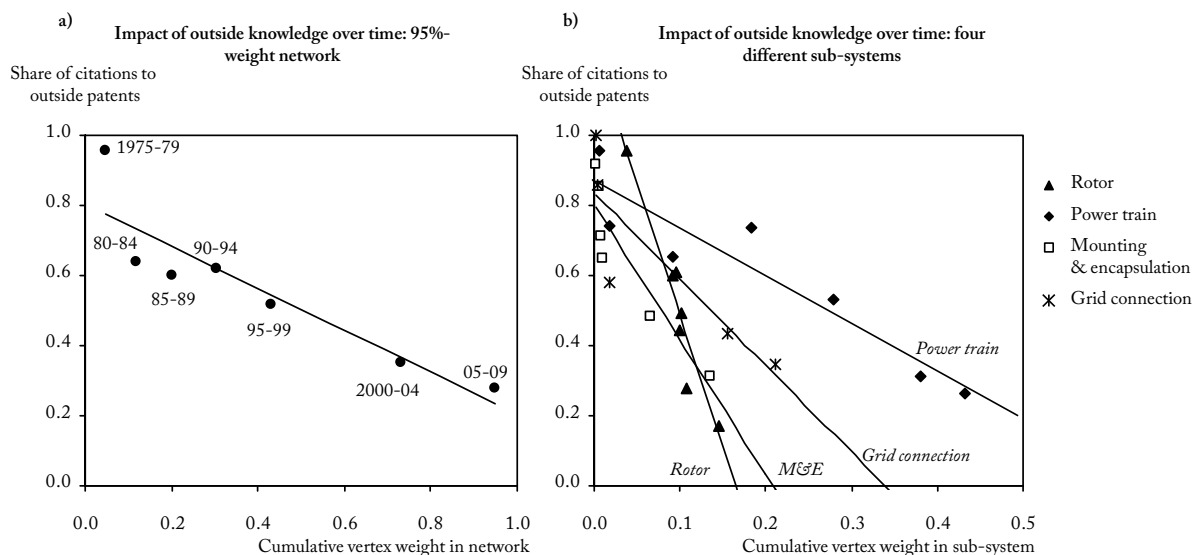


Figure 10: Declining impact of outside knowledge over time: share of citations to patents outside the network over cumulative weight. Figure a) shows the relationship for full 95%-weight network; b) shows the relationship for each of the four sub-systems separately.

6. Discussion

6.1. Creative Sequences in the Evolution of an Industry's Knowledge Base

Our results help explaining how the knowledge base of a complex product emerges and grows over time. In particular, this paper provides a model that explains how the focus of inventive activity shifts along the technological trajectory through sub-systems and components of the product, and how the impact of external knowledge evolves over time along with the shifting focus. This model holds that

the evolution of an industry's knowledge base along a technological trajectory is a *creative sequence*, with sequential changes in the focus of inventive activity and cyclical changes in the importance of industry-external knowledge, rather than a more or less linear process of incremental growth and refinement.

The principal finding of our paper is that the focus of knowledge generation shifts in a highly sequential way through the clusters of technological problems that pertain to different sub-systems of a complex product. The order underlying this creative sequence is strongly influenced by the core-periphery dimension of the design hierarchy: Our findings suggest that if a systemic artifact has many different sub-systems, inventive activity will focus first on the (core) sub-systems that are most important for the demanded service characteristics. The knowledge trajectory in the industry will stabilize once the understanding of the design of this sub-system has reached some degree of saturation. It will then gradually proceed, along the sequence defined by the design hierarchy, toward more peripheral sub-systems.²⁵ This pattern means that the design hierarchy defines not only the physical interaction of sub-systems and components in the artifact, but also structures the sequence in which the knowledge base of the industry is expanded and refined in different directions.

Our second finding is the recurring influence of outside knowledge along the creative sequence, which explains why the nested-parts dimension of the design hierarchy appears to have no influence on the trajectory of knowledge generation. Every time the focus of knowledge generation shifts to a new sub-system, a new wave of integration of network-external knowledge is initiated, starting with a high influence of network-external knowledge sourcing that gradually declines as the industry builds an independent understanding of the sub-system in focus. A deeper look at the sources of knowledge of the inventions on the trajectory suggests that the industry built upon two sources of network-external knowledge on the system and sub-system levels: industry-internal knowledge that pre-dates our observation period and industry-external knowledge. By drawing from these sources of industry-external knowledge, knowledge generation could skip levels in the hierarchy of nested parts.

The first source, industry-internal knowledge that pre-dates our analysis (even though our observation period covered roughly 50 years), explains the lack of system-level patents on today's core trajectory.

²⁵ Our data did not allow us to analyze the trajectory on the component level, but we would expect a similar pattern there.

Due to the necessarily limited time period that our database covers, the fundamental system design of horizontal axis, lift-based wind turbines, was well-established at the beginning of the observed period (even though its application to large-scale electricity generation was a novelty in the universe of artifacts). The fact that our database begins in 1963 means that system-level inventions such as US2037528 (filed in 1934) or US 2622686 (1948) cannot be located on the trajectory.

The second source, industry-external knowledge, explains the lack of patents on the sub-system level before patenting begins on the component level. The knowledge base of the wind industry builds on knowledge transferred from a number of adjacent sectors, including aerospace, electrical engineering, ship building and agricultural machinery (a list of the main involved knowledge domains is given in Table A1). Knowledge from these adjacent sectors entered the wind industry in the beginning in the form of sub-system assemblies – the power-train of a wind turbine is in principle not much different from that of a hydro turbine – as well as standardized components such as gearboxes, generators and towers. The adoption of these components in the wind industry meant an innovation in the universe of artifacts, but not necessarily novelty in the evolution of knowledge. When the focus of inventive activity later shifted toward these components (e.g., to the power train in the late 1980s), the generation of wind-specific knowledge did not start with the sub-system level, but with specific adaptations of standard components to the operational requirements of a wind turbine. Indeed, on each sub-system, the earliest patents on the core trajectory are component-level inventions that – in addition to wind-turbine patents – draw significantly on conceptual patents from other sectors. For example, MAN’s rotor patent US 4,297,076 cites water wheels (such as US 2,152,984), United Technologies’ power-train patent US 4,297,076 builds on technology from aircraft engines (US 4,330,743) and ABB’s grid-connection patent US 6,670,721 references many generic grid-related patents (such as US 6,429,546).

6.2. Implications for Technology Strategy and Public Policy

Our model of creative sequences has implications for technology strategy and public policy aimed at stimulating innovation in complex products. Both derive from the sequential pattern of knowledge creation and the influence of the design hierarchy.

The focus of an industry’s inventive activity directly affects the competitive value of knowledge held by firms and nations. Our model of creative sequences suggests that movement along the trajectory does not preclude dramatic shifts in the value of knowledge positions of firms and nations. On one

hand, at any point in time, the knowledge – codified in patents – that has a long-lasting impact on the trajectory of knowledge generation focuses on only a very narrow set of technological problems. On the other hand, this narrow focus shifts over time between sub-systems, which may depend on entirely different knowledge bases. For example, while the rotor of a wind turbine requires understanding of structural engineering, aerodynamics and materials, the power train requires knowledge of electrical engineering and electronics. This pattern may help explain sudden shifts in an industry's competitive landscape that occur without major shifts of the technological trajectory, such as the sudden rise of large electrical engineering conglomerates in the wind industry in the 2000s (including GE, Siemens, Alstom and Areva) that coincided with a shift in the focus of inventive activity toward power-train control and grid integration issues.

The notion of creative sequences also has implications for technology policy. Many governments are attempting to steer technological change in complex products to improve the competitive and environmental performance of high-technology sectors. In recent years, a particular focus has been placed on policies aimed at increasing demand for specific innovative products, such as direct financial incentives for solar PV or wind power. In the academic debate, an argument *against* such subsidies has been that market creation for emerging technologies predominantly leads to the exploitation and refinement of the *existing knowledge base*, rather than the exploration of new and potentially more radical solutions, and that this may not be enough to achieve long-term policy goals (Menanteau, 2000; Sandén and Azar, 2005; Nemet, 2009; Hoppmann et al., 2013). Our results suggest a more nuanced understanding: movement along the trajectory does not preclude the exploration of novel solutions, based on industry-external knowledge, *on the sub-system and component levels*. The development of direct-drive power trains on the sub-system level (power train) is a good example of this: although they constitute a development along the trajectory, direct-drive power trains involved the integration of industry-external knowledge of permanent magnets and full-scale power converters, and facilitated a step-change in performance (especially in terms of grid behavior). Numerous other historical examples, which include jet engines in airplanes, automatic transmissions in automobiles, the computer mouse and random access memory, also indicate that sub-system level innovations can drive major system-performance improvements. This means that if the system is sufficiently complex, movement along the trajectory driven by policy-induced demand may thus well lead to significant external knowledge sourcing and exploration of new solutions.

6.3. Interaction of Artifact and Knowledge Dimensions along Technological Trajectories

Our extension of the methodology introduced by Verspagen (2007) and others will allow researchers to study the knowledge and the artifact dimensions of technological trajectories in an integrated way. We believe that the presented methodology can yield particularly valuable insights in two directions.

First, it can be used to study the interaction between the knowledge and artifact dimensions of technological trajectories in greater detail. If data on the knowledge trajectory is systematically compared to data on product designs and market shares, further conclusions may be drawn about the mechanisms of influence between the two. In particular, future research could investigate the relative timing of shifts in the knowledge trajectory and the emergence of dominant sub-system designs in the market. Our results for the case of wind turbines suggest that different modes of innovation were prevalent in different parts of the trajectory. Interestingly, there is variation on the rotor-level of the core trajectory until 1991, while the dominant rotor design in the market (>50% from 1986) had emerged about five years earlier (cf. Figure 5 and Figure 7). This points to a non-linear model of innovation in the design of wind-turbine rotors and an important role of learning by doing and using in the early years of the industry. The shift away from the power-train level (around 1997), however, took place long before the dominant design had been established in the market (>50% from 2003). This indicates a more highly linear model of innovation in this period. The shift from a non-linear to a more linear relationship between knowledge production and artifact commercialization in the 1990s corresponds well with qualitative accounts of the wind industry (Garud and Karnøe, 2003; Hendry and Harborne, 2011; Garrad, 2012). This means that differences in learning mechanisms can be observed when comparing the evolution of knowledge and the evolution of artifacts. It also means that shifts in the predominant mode of innovation might be rooted not only in the maturation of the industry, but also in differences in the technological nature of the two sub-systems, in this case the rotor and the power train.

Second, our results suggest that the methodology can be used as a meaningful *proxy for the evolution of artifacts* along the hierarchy of control. In many cases this can facilitate a deeper look into a technological trajectory's inner dynamics, since many technological developments may be concealed when only data on design specifications in the market is examined. Patent data is relatively easy to access and process, whereas data on commercialized designs may not always be available in standardized form and sufficient detail. For example, our analysis allowed us to analyze how

knowledge generation shifted across intangible components such as wind-farm integration strategies and power train control systems.²⁶ Our results also point toward the ability to approximate the emergence of a dominant design in a specific component that cannot be easily observed statistically by analyzing the shift of the *knowledge* trajectory away from that component. Furthermore, the richness of patent data may facilitate detailed analyses of the role of different types of actors along the trajectory, as well as spatial aspects of technological evolution.

6.4. Limitations and Future Research

Two assumptions that limit the generalizability of our findings are worth noting. First, we assumed that the hierarchy of design decisions is stable over time and across countries. This assumption could be relaxed for a more detailed analysis of specific regions or time periods. On one hand, service characteristics may not always be equally important, and their weighting may depend on characteristics of customers, institutions and geographies. On the other hand, service characteristics and their weight may change over time as customers learn about technology and their needs. These limitations offer fruitful avenues for future research. Second, in identifying the trajectory of knowledge generation, we approximated it with patented inventions. This introduces a bias against knowledge that is openly shared, tacit or protected through means other than patenting. In the case of wind turbines, the knowledge pertaining to blade production in particular is typically not patented but protected as a trade secret. The fact that we found very few process patents along the trajectory may be due to a bias against process knowledge in general. Furthermore, many small wind turbine manufacturers did not patent much in the early years of the industry, possibly causing our analysis of the variation of core trajectories over time (Figure 7) to underestimate how early the industry converged on today's core knowledge trajectory.²⁷ Future research could apply qualitative methodology to capture the evolution of knowledge more holistically along the trajectory.

²⁶ Patent-citation data may also serve to identify the product architecture itself, in a methodology similar to that of Baldwin et al. (2014).

²⁷ Our analysis of the foundations of today's core trajectory, shown in Figure 8, should be unaffected by this bias because the algorithm identifies the foundations and history of today's core trajectory ex-post.

7. Conclusion

Studies of technological evolution provide ample evidence that a product's hierarchy of design decisions, or *design hierarchy*, influences the evolution of artifact designs available in the market. Much less is known about the design hierarchy's effect on the evolution of the knowledge base of an industry. For such an analysis, this paper employed the case of wind turbine technology over the period 1973–2009. We developed a methodology by linking a recently developed, quantitative approach to studying the knowledge dimension of technological trajectories to methods for studying the evolution of systemic artifacts. This novel approach allows us to relate systemic relationships between sub-systems and components in the physical artifact to patterns in the evolution of knowledge, and it may facilitate a better understanding of the interaction between the knowledge and the artifact dimensions of technological trajectories.

Our results unmask a sequential pattern in the emergence of an industry-specific knowledge base along the technological trajectory, structured by the product's design hierarchy: The trajectory of knowledge generation is marked by *creative sequences*, the focus of which shifts over time between different sub-systems, with each shift initiating a new cycle of integration of industry-external knowledge into the knowledge base.

These findings have implications for the literature on knowledge positions and competitive advantage. Whenever sub-systems of an artifact depend on different knowledge domains, windows of competitive opportunity for firms and nations with knowledge in adjacent sectors can arise *along the trajectory*, if the adjacent sector is related to the sub-system that moves into the focus of innovation. In other words, what constitutes a good knowledge position to enter a specific industry may change significantly over time. This may help explain – and even anticipate – shifts in the competitive landscape that occur in the absence of discontinuities in the trajectory.

Our findings also have implications for the literature on the innovation impact of demand-side policies. The pattern of creative sequences implies that public policy-driven incentives that induce movement *along* a technological trajectory – rather than stimulating *new* trajectories – may not only induce the exploitation and refinement of existing knowledge, but also induce the exploration of new knowledge and concepts on the sub-system and component levels of the design hierarchy.

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Appendix

Table A1: Wind-specific engineering tasks and main involved knowledge domains

Components	Engineering tasks	Main knowledge domains
Rotor		
Blades	Aerodynamic and structural design of rotor to capture wind energy	Aerodynamics; structural dynamics
	Design of non-destructive testing equipment and procedures	Optics; robotics; mechanical engineering
	Development of tailored structural materials and coating	Materials science; chemistry
	Processing of large-scale composite components and core materials	Chemical, mechanical and thermal process engineering; automation engineering
	Design of equipment and routines for transport and installation of rotor blades	Logistics, mechanical engineering
Hub	Structural design and integration of O&M and control features	Aerodynamics; structural dynamics
Rotor control system (pitch and yaw mechanisms), control routines	Design of rotor control strategy and software	Aerodynamics; control engineering, software engineering
	Design and integration of electric motors, gears, hydraulics and power sources	Electrical, mechanical, and control engineering
Power train		
Mechanical drive-train: Rotor shaft, bearings, gearbox, couplings	Design of drive-train architecture	Mechanical engineering
	Dimensioning and material selection for hub, bearings, shafts, brakes, gearbox, lubrication, joints and couplings	Material science; structural dynamics
Electrical drive-train: generator, power electronics	Design of generator topology	Electrical engineering, electronics
	Design and dimensioning of generator, power electronics, and cooling systems	Electrical engineering; electronics, thermodynamics
Power-train control system and routines	Design of rotor control strategy and software	Aerodynamics; control engineering, software engineering
	Design and integration of switch board, sensors, actuators (e.g., brakes) and power sources	Electrical, mechanical, and control engineering

Table A1 (continued): Wind-specific engineering tasks and main involved knowledge domains

Mounting & encapsulation		
Nacelle, spinner and bedplate	Design of load transfer, noise insulation and thermal management	Mechanics; acoustics; thermodynamics
	Aesthetic and aerodynamic design	Industrial design; aerodynamics
Tower	Choice of tower shape, modularity, and structural materials	Materials science
	Dimensioning against bending and fatigue	Structural dynamics; mechanical engineering
Foundation	Dimensioning for static and dynamic load transfer	Mechanics; civil engineering
Climate & vibration control system and routines	Design of control strategy and software	Thermodynamics; structural dynamics; control and software engineering
	Design and integration of dampers, sensors and climate conditioning system	Thermodynamics; control engineering
Grid connection		
Transformer / substation and power cables	Design of wind-farm circuitry, voltage transfer, electrical insulation	Electrical engineering
Storage	Choice and design of storage technology	Electrical engineering, electronics
Grid-impact and wind-farm control system and routines	Design of control strategy and software	Electrical, control and software engineering
	Design and integration of control system elements	Electronics; control engineering

Table A2: Design options within the product architecture of horizontal axis wind turbines operating on the lift principle

Salient design features	Design options (today's most common design in bold)
Wind turbines (system-level)	Vertical axis, horizontal axis ; drag-based, lift-based energy extraction
Rotor	
Rotor position relative to power train and tower	Facing the wind (upwind) , facing away from the wind (downwind)
Rotor size	5-160 m diameter (~100 m)
Number of blades	1, 2, 3, many
Rotor speed control	Aerodynamic ('stall-controlled'), rotation of blades around own axis to control lift ('pitch'), hybrid forms
Rotor orientation control	Yaw drive , positioning vane
Rotor material	Glass fiber reinforced plastics , carbon fiber reinforced plastics, wood composites, aluminum, steel
Rotor fixation	Fixed , hinged, teetered
Power train	
Number of bearings	1, 2, 3
Mechanical transmission	Gearbox , without gearbox ('direct drive')
Number of transmission ratios ('speeds')	1-5 fixed speeds, variable speed
Number of generators	1-4
Generator size / type	5 kW – 7.5 MW (~3 MW) / asynchronous (wound rotor, squirrel cage) , synchronous (permanent, wound rotor)
Power converters (rectifier & inverter)	Full, partial , none
Mounting & encapsulation	
Nacelle / spinner	None, reinforced-plastic cover
Tower structure / height	Tubular , lattice / 20-130 m (~100m)
Foundation	Concrete slab, pile
Grid connection	
Storage	None , battery storage, compressed-air storage
Grid-integration control	None, fault ride-through capability, power control capability

Table A3: Goodness-of-fit test of distribution of patent citations from sub-system i to sub-systems $j=1\dots 4$ with a null hypothesis that the distribution of citations follows the distribution of possible recipient patents (citations to system-level patents were excluded).

Citations from patents categorized into sub-system...	N	Degrees of freedom	χ^2	p
Rotor	400	3	271	<0.001
Power train	885	3	318	<0.001
Mounting & encapsulation	651	3	458	<0.001
Grid connection	886	3	555	<0.001

Table A4: Design hierarchy, as determined by relationship between components (rows) and un-weighted service characteristics (columns)

System / sub-systems / components	Initial cost		Reliability & durability		Electrical characteristics		Environmental impact		Others		Pleiotropy ^b	Hierarchy of nested parts / Hierarchy of control ^c
	Turbine cost	Cost of transport, installation & disassembly	Availability & O&M cost	Lifetime	Power curve	Grid behavior	Visual impact	Noise emissions	Operational safety	Suitable climate conditions		
Wind turbine (system-level)	X ^a	X	X	X	X	X	X	X	X	X	10	1
Rotor	X	X	X	X	X	X	X	X	X	X	10	2/A
Rotor blades	X	X	X	X	X	X	X	X	X	X	10	3
Hub		X	X	X	X					X	5	3
Rotor control	X		X	X	X	X		X	X	X	8	3
Power train	X	X	X	X	X	X		X	X	X	9	2/B
Mechanical drive-train	X	X	X	X	X	X		X	X	X	9	3
Electrical drive-train	X	X	X	X	X	X		X	X		8	3
Power-train control			X	X	X	X		X	X	X	7	3
Mounting & encapsulation	X	X	X		X		X	X	X	X	8	2/C
Nacelle, spinner & bedplate		X	X		X		X	X		X	6	3
Tower	X	X			X		X				4	3
Foundation		X			X						2	3
Climate and vibration control			X					X	X	X	4	3
Grid connection	X		X		X	X		X	X		6	2/D
Transformer / substation and power cables	X		X		X	X		X	X		6	3
Storage (if applicable)	X		X			X			X		4	3
Wind-farm and grid-integration control			X		X	X			X		4	3

^aEach x represents a significant influence of the respective sub-assembly or the individual component (in rows) on the main service characteristic (in columns); ^bThe pleiotropy is the count of influences per row. ^cThe number of the design hierarchy indicates the hierarchy of nested parts (1=system, 2=assembly of components, 3=component); the capitalized letter indicates the hierarchy of control on each level (A=highest pleiotropy, B...D sorted accordingly)

Table A5: Patents along critical path of wind-patent citation network 1973-2009

Priority patent	Application	Focus of invention	Focus in hierarchy	Assignee	Assignee type
SE 005,407	12-May-75	Blade with integrated over-speeding control mechanism	Rotor	Svenning Konsult AB	Engineering consultancy
DE 2,655,026	4-Dec-76	Rotor-hub arrangement with teetering hub and two blades	Rotor	U. Huetter (Indiv.)	Public sector (university)
US 4,297,076	8-Jun-78	Control system for two-bladed rotor with adjustable tips	Rotor	MAN	Turbine manufacturer
US 4,274,807	31-Jul-78	Three-bladed turbine with hydraulic pitch mechanism	Rotor	C E Kenney (Indiv.)	Individual
US 4,366,387	10-May-79	Two-bladed downwind turbine with teetering hub and aerodynamic pitch mechanism	Rotor	Carter Wind Power	Turbine manufacturer
US 4,435,646	24-Feb-82	Rotor with teetered hub and mechanical pitch control system	Rotor	North Wind Power	Turbine manufacturer
US 4,565,929	29-Sep-83	Two-blade turbine with novel drag brake and control system	Rotor	Boeing	Turbine manufacturer
US 4,703,189	18-Nov-85	Torque control system for variable-speed power train	Power train	United Technologies	Turbine manufacturer
US 4,700,081	28-Apr-86	Operation strategy for variable-speed power train	Power train	United Technologies	Turbine manufacturer
US 5,083,039	1-Feb-91	Variable-speed power train architecture and power control	Power train	US WindPower	Turbine manufacturer
US 5,155,375	19-Sep-91	Speed control system for variable-speed power train	Power train	US WindPower	Turbine manufacturer
US 5,652,485	6-Feb-95	Fuzzy-logic power train control for variable wind conditions	Power train	U.S. EPA	Public sector (regulatory agency)
US 6,137,187	8-Aug-97	Variable-speed power train architecture and power control	Power train	Zond Energy Systems	Turbine manufacturer
US 6,566,764	23-May-00	Variable-speed power train adapted to smoothen power output	Power train	Vestas Wind Systems	Turbine manufacturer
US 6,670,721	10-Jul-01	Inverter control system for grid-friendly power output	Grid connection	ABB	Component supplier (generator)
DE 1,048,225	28-Sep-01	Collective control method for turbines in a wind farm	Grid connection	Enercon	Turbine manufacturer
US 7,190,085	8-Apr-03	Variable-speed power train architecture	Power train	Alstom	Component supplier (generator)
US 7,042,110	7-May-03	Variable-speed power train architecture	Power train	Clipper Windpower	Turbine manufacturer
US 7,205,676	8-Jan-04	Generator control optimizing response to grid failure	Grid connection	Hitachi	Turbine manufacturer
JP 055,515	27-Feb-04	System to control nacelle vibrations	Mounting & encapsulation	Mitsubishi Heavy Ind.	Turbine manufacturer

US 7,309,930	30-Sep-04	System to control turbine vibrations	Mounting & encapsulation	General Electric	Turbine manufacturer
US 7,342,323	30-Sep-05	Power train control routine based on upstream wind measurements	Power train	General Electric	Turbine manufacturer
US 7,400,055	1-Feb-06	Control routine to suppress tower vibrations	Mounting & encapsulation	Fuji Heavy Industries	Turbine manufacturer
US 7,851,934	14-Sep-06	Control routine to respond to grid faults	Grid connection	Vestas	Turbine manufacturer
US 7,911,072	14-Sep-06	Control routine to respond to grid faults	Grid connection	Vestas	Turbine manufacturer
US 7,714,458	22-Feb-08	Control routine to respond to grid-side load shedding	Grid connection	Nordex	Turbine manufacturer
US 7,949,434	16-Jun-08	Control system for wind farm with redundant control unit	Grid connection	Nordex	Turbine manufacturer

Table A6: Shifting focus in hierarchy of control along trajectory of knowledge generation, indicated by share of vertex weight in 95%-weight network in different elements of the system (number of patents in parentheses)

	1975-1979	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004	2005-2009
Wind turbine (system-level)	0.02 (2)	0.00 (1)	0.04 (3)	0.07 (3)	0.08 (3)	0.00 (2)	0.01 (4)
Rotor	0.77 (12)	0.76 (17)	0.05 (7)	0.04 (2)	0.01 (3)	0.02 (11)	0.18 (60)
Power train	0.13 (5)	0.16 (5)	0.91 (8)	0.87 (8)	0.78 (14)	0.34 (39)	0.23 (67)
Mounting & encapsulation	0.04 (1)	0.05 (3)	0 (0)	0.02 (2)	0.03 (8)	0.18 (20)	0.32 (67)
Grid connection	0.04 (1)	0.04 (1)	0 (0)	0 (0)	0.10 (6)	0.46 (4)	0.25 (75)

Technology Life-Cycles in the Energy Sector – Technological Characteristics and the Role of Deployment for Innovation[‡]

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Abstract

Understanding the long-term patterns of innovation in energy technologies is crucial to inform public policy planning in the context of climate change. We analyze which of two common models of innovation over the technology life-cycle – the product-process innovation shift observed for mass-produced goods or the architecture-component shift observed for complex products and systems – best describes the pattern of innovation in energy technologies. To this end, we develop a novel, patent-based methodology to study how the focus of innovation changed over the course of the technology life-cycle. Specifically, we analyze patent-citation networks in solar PV and wind power in the period 1963-2009. The results suggest that solar PV technology followed the life-cycle pattern of mass-produced goods – early product innovations were followed by a surge of process innovations in solar cell production. Wind turbine technology, in contrast, more closely resembled the life-cycle of complex products: the focus of innovative activity shifted over time through different parts of the product, rather than from product to process innovations. These findings indicate very different innovation and learning processes in the two technologies and the need to tailor technology policy to technological characteristics, and help conceptualizing previously inconclusive evidence about the impact of technology policies in the past.

Keywords: Technology life-cycle, energy technology, patents, citation network analysis, wind power, solar PV

Highlights:

- We develop a patent-based methodology to study technology life-cycles.
- We apply the methodology to solar PV and wind power over the period 1963-2009.
- PV followed the life-cycle of mass-produced goods and commodities.
- Wind power followed the life-cycle of complex products and systems.
- We develop a typology of energy technologies and discuss policy implications.

1. Introduction

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). Better understanding the long-term patterns of innovation in energy technologies is therefore crucial to inform public policy planning (Grubb, 2004; Pielke et al., 2008; Grubler, 2012), and a growing body of literature is studying innovation processes and technology policy in the energy sector (e.g., Anadon, 2012; Gallagher et al., 2012; Grubler and Wilson, 2014). It is a particularity of the energy sector that technologies from a diverse range of sectors of the economy are employed in the extraction, conversion and end-use of energy. Therefore, most energy innovations are not developed by energy utilities, but enter the sector embodied in specialized equipment or innovative fuels from other sectors, such as semiconductors (solar cells), electro-mechanical machinery (gas turbines), agriculture (biofuel feedstock) and biochemistry (biofuel conversion) (Markard, 2011; Wiesenthal et al., 2011). Some of these energy technologies are large capital goods, such as biomass power plants, while others are modular and produced in large volumes, such as heat pumps (Neij, 1997). Some are very specific to local geographies, such as geothermal power plants, while others are globally applicable almost without adaptation, such as solar cells (Huenteler et al., 2014a). Yet so far only few studies have investigated systematically how innovation processes differ between energy technologies originating in different sectors, and explored the implications for energy technology policy (Norberg-Bohm, 2000; Trancik, 2006; Wilson, 2012; Winskel et al., 2014).

There is a rich empirical literature describing how innovation processes differ between sectors in general (Pavitt, 1984; Marsili, 2001), with a particular focus on different *temporal patterns* of innovation (Rosenberg, 1982; Dosi, 1988; Dosi and Nelson, 2013). For example, cross-sectoral comparisons present evidence that patterns of innovation over the technology life-cycle differ between *mass-produced goods* and *complex capital goods* (Hobday, 1998; Davies and Hobday, 2005; Magnusson et al., 2005). In mass-produced goods, the focus of innovative activity tends to shift over time from *product* to *process innovations* as one dominant design is adopted throughout the industry and the general thrust of R&D shifts toward increasing automatization of the production process (Vernon, 1966; Abernathy and Utterback, 1988; Peltoniemi, 2011). This is accompanied by an increasing role for learning-by-doing in production over time (Hatch and Mowery, 1998). In complex products and systems, such as aircraft, trains or nuclear plants, in contrast, a shift toward large-scale production is extremely rare; instead, the focus of innovative activity tends to shift from the *system architecture*

towards individual *sub-systems* or *components* (Miller et al., 1995; Davies, 1997; Murmann and Frenken, 2006). In these cases, learning-by-using and user-producer interaction remain important even for mature technologies (Rosenberg, 1982).

The two contrasting models of innovation in mass-produced goods and complex products and systems describe, in a stylized way, different drivers of innovation and mechanisms of learning in *later stages* of the life-cycle. They thus have important implications for the design of technology policies for clean energy technologies, many of which seek to induce innovations and cost reductions in *relatively mature* technologies – most clean technologies supported today, including wind, solar and biomass, have been first deployed at scale in the wake of the oil crises in the 1970s and 80s and are now in later stages of the technology life-cycle. However, much of the technology policy debate today on the on innovation in these technologies is centered on *learning-by-doing* in manufacturing and *economies of scale*, reflecting a mental model heavily influenced by the life-cycle model for mass-produced goods.²⁸

Most of the currently supported clean energy technologies are somewhere between the two extremes. Unlike commodities and mass-produced consumer goods, the designs of wind turbines, solar PV systems, fuel cells or electric vehicles all feature a number of different sub-systems and components, and continue to evolve even after their first large-scale deployment. But unlike complex products and systems they are also produced in significant volumes. In order to stimulate innovation in these technologies effectively, we need to better understand the processes of innovation in later stages of the technology life-cycle. However, researchers have so far paid relatively little attention to the question whether patterns of innovation differ significantly over the life-cycle of technologies in the energy sector. To address this gap, this paper develops a patent-based methodology to analyze which of the two models of the technology life-cycle – the product-process innovation shift observed for mass-produced goods or the architecture-component shift observed for complex products and systems – best describes a pattern of innovation over time and apply this methodology to the two most rapidly growing clean energy technologies: solar photovoltaics (PV) and wind power.

²⁸ For example, the German feed-in tariff for solar power (a form of subsidized electricity tariff), with about \$10bn per year currently the largest deployment policy in the world, was designed as "market entry assistance to allow for cost reductions, which will then facilitate the diffusion of photovoltaic through the market" (German Federal Diet, 1999). The US tax credit under the U.S. 'Recovery Act' in 2009 had the objective "to help renewable energy technologies achieve economies of scale and bring down costs" (The White House, 2009).

The paper proceeds as follows. Section 2 introduces two alternative models of the technology life-cycle and discusses the main technological determinants of life-cycle patterns discussed in the literature. Section 3 introduces the two case technologies – solar PV systems and wind turbines – and presents key indicators of progress along the technological trajectory, such as cost and efficiency, over the last five decades. In section 4, we introduce a novel methodology to study how the focus of innovative activity evolved along the trajectories of the two case technologies. The results are presented in section 5 and their implications discussed in section 6. Section 7 summarizes the main conclusions.

2. Theoretical Perspective and Literature Review

The ‘life-cycle’ metaphor has been used in many different contexts in research on the management and economics of innovation (Routley et al., 2013). This paper draws on the literature that uses the term life-cycle to describe the *temporal patterns of technological innovation* in an industry, in particular the emergence of dominant designs and architectures and the corresponding *shifts in the focus of innovation*, observed across a wide range of technologies (Utterback and Abernathy, 1975; Abernathy and Utterback, 1978; Clark, 1985; Utterback and Suárez, 1993; Murmann and Tushman, 2002; Murmann and Frenken, 2006; Lee and Berente, 2013).

2.1. Two Contrasting Models of the Technology Life-Cycle

Technological evolution in manufactured products often takes a cyclical form, with an early stage marked by intense product innovation and competition among fundamentally different product concepts (Anderson and Tushman, 1990; Suarez and Utterback, 1993; Murmann and Frenken, 2006). After a *dominant design* has emerged, technological change becomes cumulative and incremental as innovation proceeds along ordered *technological trajectories* (Dosi, 1982; Mina et al., 2007; Verspagen, 2007; Fontana et al., 2009; Bekkers and Martinelli, 2012).

The most influential model of temporal patterns of innovation holds that technological trajectories are punctuated by technological discontinuities which initiate cycles of *product* and *process* innovation (e.g., Vernon, 1966; Utterback and Abernathy, 1975; Abernathy and Utterback, 1978, 1988; Utterback and Suárez, 1993). Initially, the focus of the innovative activity in the industry is on product innovation, as firms try to exploit the performance potential of the discontinuous innovation and compete in the market with many alternative product designs. This ‘era of ferment’ culminates in a dominant design as the technology’s core components become standardized. What follows is an ‘era of incremental

change', during which the technology proceeds along defined trajectories and the focus of innovative activity is on process innovations and specialized materials, as firms compete primarily on the basis of costs – until a new discontinuity re-ignites design competition (see Figure 1a). The shift from product to process innovations is due in part to standardization of product design feature, but also the result of a transition from the era of ferment to the era of incremental change is also characterized by a shift from small-batch production to mass production, and from general-purpose plants to large manufacturing facilities with highly specialized production equipment (see Table 1) (Abernathy and Utterback, 1988).

The Abernathy-Utterback (A-U) model has been extremely influential²⁹, but several authors, including Miller et al. (1995) and Davies (1997), note that the model is valid only for a subset of technologies. In particular, empirical studies of innovation in complex, capital-intensive goods demonstrate that many high-value, high-technology products, so-called *complex products and systems*, never reach a phase of process innovation and mass production and innovative activity remains focused on product innovation throughout the life-cycle (see Table 1) (Davies, 1997; Hobday, 1998; Davies and Hobday, 2005). This is in line with studies of the era of incremental change which found in many cases little evidence for a decline in product innovations (Gort and Klepper, 1982; Henderson, 1995; Lee and Berente, 2013).

Based on this evidence, Davies (1997) introduces a model of innovation over time that characterizes the life-cycle of complex products as one where the product-process shift observed for mass-produced goods is replaced by a shift from innovation in the system architecture to waves of innovation in sub-systems and components (see Figure 1b) (Davies, 1997; Davies and Hobday, 2005). As in the A-U model, the early phase is characterized by a focus on functional performance and product innovations. However, the competitive emphasis is not on specific designs but on innovations in the *product architecture*, which allocate system functions to the individual components and defines the interfaces between them (e.g., Clark, 1985). After the emergence of a dominant product architecture and standardized core sub-systems (the dominant design), innovation along the technological trajectory is focused on individual sub-systems and components (Murmann and Frenken, 2006). For example, after the emergence of the turbojet engine as the dominant propulsion system, innovative activity in the aircraft industry focused on improving the airframe and parts of the engine, such as compressor blades,

²⁹ The two seminal works (Utterback and Abernathy, 1975; Abernathy and Utterback, 1978) had a total of 6,544 google scholar citations between them on 12/6/2014.

rather than shifting toward process mechanization and automatization (Constant, 1980). Over time, changes in sub-systems and components may create performance imbalances and thus require changes in other parts of the system (Brusoni et al., 2001; Funk, 2009), in which case Davies refers to them as ‘systemic innovations’ (see Figure 1b).

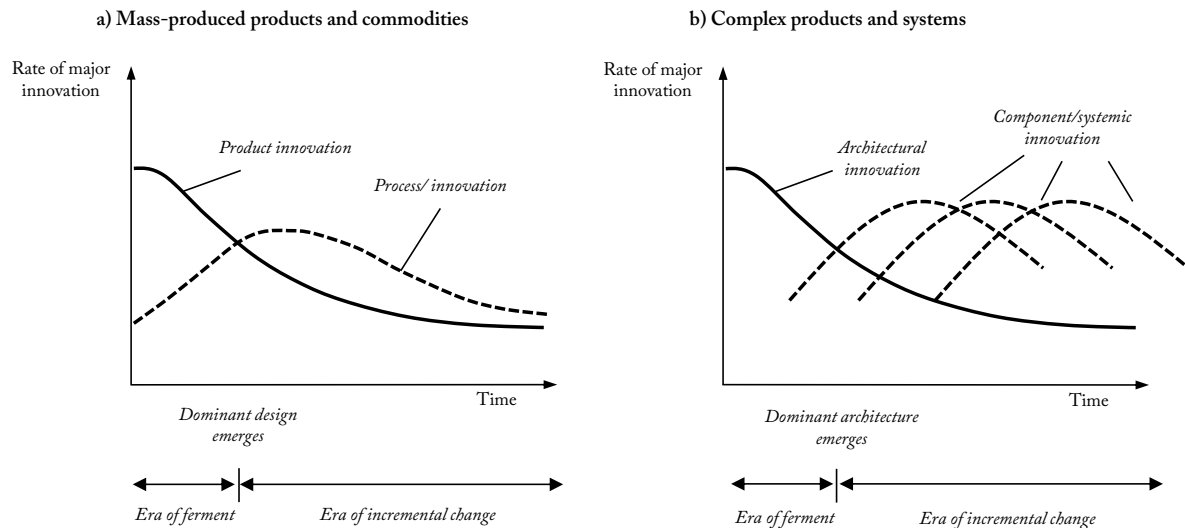


Figure 1: Two contrasting models of innovation over the technology life-cycle: a) mass-produced goods; b) complex products and systems (Abernathy and Utterback, 1988; Davies, 1997).

	Era of ferment		Era of incremental change	
	Mass-produced goods		Complex products and systems	
Competitive emphasis on ...	Functional product performance	Cost reduction	Functional product performance	
Innovation stimulated by ...	Revealed user needs and users' technical inputs	Pressure to reduce cost and improve quality	Evolving user needs as well as internal and external technical opportunities	
Product line	Diverse, often including custom designs	Mostly undifferentiated standard products	Product variations that share common architecture but are customized to user needs	
Predominant type of innovation	Frequent major product innovations	Incremental innovation in processes and materials	Sequences of systemic and incremental component changes	
Important sources of knowledge	Product R&D, learning-by-doing and learning-by-using	Process R&D, learning-by-doing	Product R&D, learning-by-using	
Plant	General-purpose plant located near user or source of technology	Large-scale plant tailored to particular product designs to realize economies of scale	General-purpose plant with specialized sections located near user or source of technology, little emphasis on economies of scale	
Production process	Flexible and inefficient: major changes easily accommodated	Efficient, capital-intensive, and rigid: cost of change is high	Remains flexible: individual projects or small-batch production	
Production equipment	General-purpose equipment, requiring highly skilled labor	Special-purpose, mostly automatic with labor tasks mainly monitoring and control	Some sub-processes automated, but mostly requiring highly skilled labor	

Table 1: Characteristics of the innovation and production processes in the two alternative models of the technology life-cycle (Abernathy and Utterback, 1988; Davies, 1997).

The two models differ most significantly in their characterization of innovation along the technological trajectory after a dominant design or product architecture has emerged (see Table 1). Three aspects are particularly important to characterize innovation and learning processes in the era of incremental change: First, with regard to the *type and breadth of innovative activity*, the A-U model predicts a surge in process innovations and a relatively narrow focus on cost reductions through improved production processes. The Davies model describes a steady stream of product innovations as well as a broadening of the focus from the system architecture and core sub-systems to a broader range of sub-systems and components, with an emphasis on understanding and enhancing the complex interactions between different elements of the system. Second, the A-U model ascribes an important role to the exploitation of *economies of scale* to realize cost reductions, which implies a role for *learning-by-doing in manufacturing* (e.g., Hatch and Mowery, 1998). Davies' model, in contrast, sees the later stage of the life-cycle as still characterized by small-scale, flexible production plants that allow limited learning-by-doing and economies of scale. And third, with regard to the *role of performance uncertainty and learning-by-using*, the A-U model predicts a rapid decline in uncertainty about the functional performance of different design features and user needs. This results in very little need in the innovation process for experience from large-scale or long-term experimentation and user-producer interaction, which allows moving factories to locations with cost advantages even if they are far from the actual users (e.g., Vernon, 1966). This is in stark contrast to the continued dependence on learning-by-using and close proximity between users and producers that characterizes complex products and systems (e.g., Rosenberg, 1982).

2.2. Technological Characteristics and Life-Cycle Patterns

How can one locate specific technologies in the continuum created by the two described life-cycle models? In the literature on complex products and systems, the term 'complex' refers to a large number of drivers, e.g., the number of customized components, the scale of the product and the intensity of regulatory involvement in the specification of requirements (Hobday, 1998). When comparing the patterns of innovation over the life-cycles, Davies (1997) narrows these drivers down to four main characteristics of complex products and systems vis-à-vis mass-produced goods: (i) the *complexity of product architecture*, (ii) the *scale of the production process*, (iii) the *market structure* (oligopoly versus mass market) and (iv) the *degree of government involvement* in technological evolution (which is often unusually high for complex products and systems).

When applying these characteristics to the energy sector, these determinants can be further reduced to two underlying technological characteristics. On the one hand, the evolution of all energy technologies are heavily affected by government policies, e.g., in the form of technology standards, environmental regulations, subsidy schemes and industrial policy. On the other hand, for energy technologies the scale of the production process is highly correlated with the market structure, since low-volume technologies are typically procured by large, regulated utilities (wind power plants, electricity grids), indicating a bilateral oligopoly, whereas mass-produced energy technologies are mostly used by consumers, either in the form of end-use technologies (e.g., heating systems or electric cars) or as decentralized, small scale energy systems (solar PV systems, solar water heaters). This leaves two main technological determinants of life-cycle patterns in the energy sector:

1. *The complexity of the product architecture*, understood here as a driven by the number of sub-systems and components and the complexity of their interactions in the system. On the one hand, a complex product architecture implies many opportunities to improve individual elements and their interaction after the emergence of a dominant design. At the same time, architectural complexity is a driver of iterations and learning-by-using in the innovation process, because it makes performance features of the final product difficult to predict (Rosenberg, 1982; Nightingale, 2000).
2. *The scale of production process*, which is mainly driven by the modularity of the system as well as the size and homogeneity of user demand. A large process scale implies many opportunities to improve cost and functional performance through process innovations. At the same time, it often requires a prolonged process of experimentation and learning-by-doing to develop and operate the large-scale production systems with many interdependent process steps (e.g., Hatch and Mowery, 1998).

The two characteristics span a technology space in the energy sector, with the two life-cycle models as two extremes (see Figure 2). However, the models have been developed based on contrasts between vastly different technologies (e.g., infrastructure systems versus light bulbs), while most energy technologies have relatively complex designs *and* are produced in non-trivial numbers – i.e., fall somewhere in between the extremes. It is therefore not entirely clear where different types of energy technologies are located on the displayed continuum. In the following sections this paper analyzes two technologies with the aim to locate them in the matrix displayed in Figure 2. We show that important characteristics known for the A-U model and the Davies model can be observed when dissecting the innovation patterns in energy technologies over time.

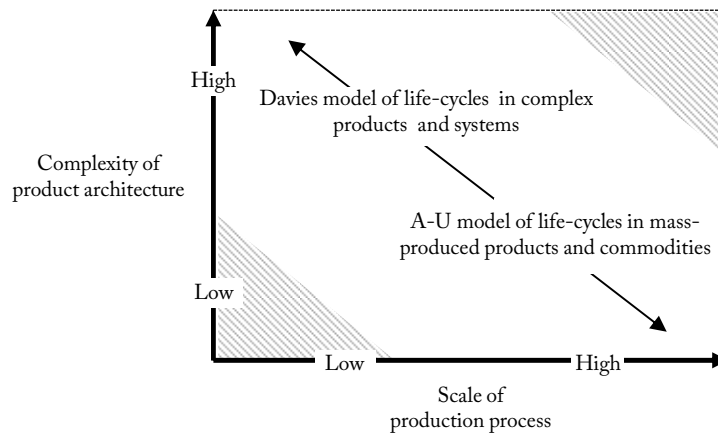


Figure 2: Technology space in the energy sector, spanned by the scale of the production process and the complexity of the product architecture.

3. Research Cases

This paper explores if life-cycle patterns differ significantly between technologies in the energy sector. The cases analyzed for this purpose need to fulfil two main criteria. *First*, they need to differ in the two determinants of life-cycle patterns identified above: the complexity of the product architecture and the scale of the production process. *Second*, they need to be in the era of incremental change, during which the differences we seek to identify become salient.

Wind power and solar PV were selected because they fulfil these criteria: They exhibit different degrees of complexity and different scale of production, as will be discussed in section 3.1. And both have a dominant design and are now in the era of incremental change (see in section 3.2). Last but not least, the two cases are highly relevant for public policy: solar PV and wind power are projected to receive \$1.7 trillion and \$1.1 trillion in subsidies, respectively, over the period 2013-2040 (IEA, 2014). A better understanding the processes of innovation and technological evolution in these technologies can therefore inform important technology policy decisions in the coming decades.

3.1. Characteristics of the Case Technologies

To delimit the empirical scope of our analysis, we understand the term ‘technology’ as describing a class of artifacts defined by a common ‘operational principle’ and the pertaining procedures and elements of knowledge (Polanyi, 1962; Vincenti, 1990; Murmann and Frenken, 2006). We considered solar PV to include all technology related to power generation using the photovoltaic effect, and wind power to include all technology using lift forces of the wind to generate electricity. Table 2, which

presents the elements of solar PV and wind power systems and their functions in the system, illustrates how the central role of these two physical principles in the functional structure of the electricity generation systems. A *dominant design* is understood here as a standard in design of the technology's core components (Murmann and Frenken, 2006), which we define here as the rotor in a wind turbine and the cell concept of a PV system.

When comparing the technology characteristics that indicate patterns in the technology life-cycle (see section 2.2) between the two technologies, it becomes evident that *the complexity of the product architecture* is significantly higher for wind turbines, while the *scale of the production process* is higher in the case of solar PV.

Solar PV systems are modular systems that consist of small generating units – the solar *cells* – which are connected to modules of around 200W and integrated with mounting and tracking structures and, in order to feed the electricity into the grid, inverters and control systems (see Table 2). Solar modules have only few components and no moving parts, and currently cost about 150-250\$ at the factory gate, depending on the exact capacity rating, efficiency, and other features such as warranties. The fact that a solar module contains few moving parts is reflected in a very low value of operation and maintenance (O&M) cost, which are often below 1% and rarely exceed 5% (Moore and Post, 2008). Solar cells are produced, in batches of at least several thousands, on large and specialized, automated production lines which cost up to several billion USD. Consequently, the market for solar modules exhibits many features of mass-manufactured commodities – even spot markets for cells and modules (e.g., Barua et al., 2012).

Modern wind turbines, in contrast, are electro-mechanical machines that can reach up to 8 MW of electric capacity, consist of several thousand components and cost up to \$15 million per unit (a list of key sub-systems and main functions is given in Table 2). Although they are typically not made-to-order, wind turbines often contain site specific characteristics, such as sand and dust in the air, high altitude sites or very cold climate. The high number of moving key components is reflected in high O&M cost, which make up 20-25 % of the cost of electricity over the lifetime of a wind turbine (Twidell, 2009). Wind turbine production and construction processes are dominated by what one of our interviewees called “simple industrial craftsmanship”, i.e., standard industrial processes that require skilled manual labor and are performed on multi-purpose machinery, such as welding, milling and drilling machines. Specialized equipment is used only in the blade manufacturing and installation processes, in the form of large moulds and cranes. Overall, a wind turbine production facility has

construction cost in the order of \$20–200 million, depending on annual production capacity, and can produce up to several 100 MW of turbines per year. Further detail is given on both technologies in Table A1 and Table A2 in the appendix, which show the main engineering tasks in the two technologies, as well as the main areas where a technology-specific body of knowledge has emerged.

Table 2: Product architectures of solar PV and wind power systems, showing the main sub-systems and their function in the technological system.

System	System element	Function
Solar PV system	Solar cell	Absorption of solar irradiation and conversion into electric current through <i>photovoltaic effect</i>
	Solar module	Connection of 'string' of cells to achieve desired output voltage; protection of cell from moisture and structural damage; insulation of electrical current
	Mounting system	Integration of modules into larger structures (array); load carrying and transfer (mounting system); integration of module / cells into building environment (building integration); reorientation of modules / array to follow the sun (tracking system)
	Grid connection	Conversion of DC current into AC (inverter); reduction of impact of grid-side disturbances; maintenance of grid-friendly system output (electrical control system)
Wind power system	Rotor	Conversion of wind energy into rotational energy through <i>lift effect</i> (rotor blades); transfer of energy to main shaft (hub); adjustment of rotor and individual blades to wind & system conditions (rotor control system)
	Power train	Transmission of rotational energy from rotor to generator, including adjustment of rotational frequency (mechanical drive train); conversion of rotational energy into electrical energy, AC-DC conversion and frequency conversion (electrical drive train); adjustment of power-train elements to wind & system conditions (power-train control)
	Mounting & encapsulation	Load carrying and machinery enclosure (nacelle, spinner, bedplate); support turbine at designated height and load transfer to foundation (tower); load transfer into ground (foundation); regulation of operating conditions & minimization of system vibrations (climate and vibration control)
	Grid connection	Transfer of electrical energy to grid (transformer/substation, power cables); storage of electrical energy (storage system, if applicable); reduction of impact of grid-side disturbances; maintenance of grid-friendly wind farm output (grid-impact and wind-farm control)

3.2. Dominant Designs and Technological Trajectories in Solar PV and Wind

Power

This section presents evidence for the fact that both technologies gone through different stages of the life-cycle and are now the era of incremental change, by demonstrating (i) the presence of *dominant designs* in solar PV and wind power and (ii) the maturity of the industries and the prevalence of cumulative and incremental innovation.

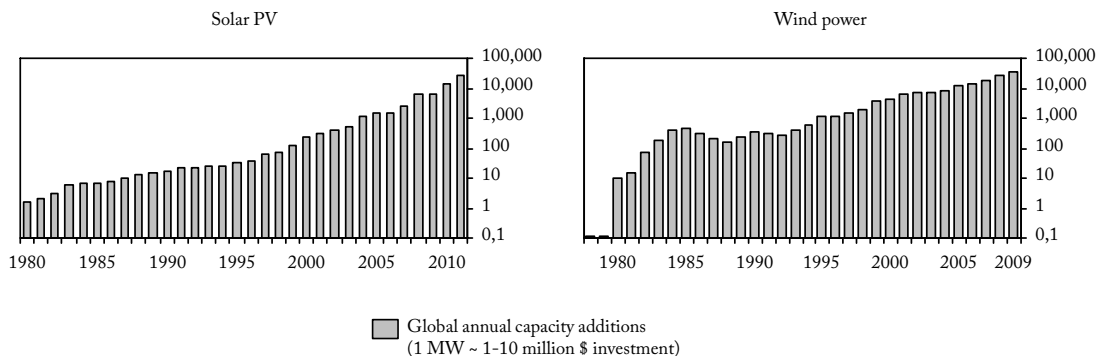
The market for solar PV and wind power systems has grown exponentially over the last four three decades. As a comparable indicator for market growth, Figure 3b shows annual installations for the two technologies (very roughly, one MW of installations translates into \$1-10m of investment). The data illustrates that both industries have now grown to large and mature industries: In 2012, the PV industry recorded sales of around \$80bn and the wind industry of around \$75bn (Pernick et al., 2013). Wind power had a head start with early installations in California during the 1980s, and a continued boom since around 1995. But the market for solar PV has caught up in the last decade, and now exhibits similar absolute annual installations rates. The IEA reckons total spending on deployment subsidies to be in the range of \$25bn for solar PV and \$21bn for wind power (IEA, 2013). The maturity of the industries is further demonstrated by the high relative share of corporate R&D expenditures of total R&D in the two industries, which stands at 58% in solar PV and 76 % in wind power (Wiesenthal et al., 2011).

With the growing market, dominant designs emerged in both industries in the early 1990s (solar PV) and late 1980s (wind power), as shown in Figure 3b. For solar PV, the chart displays market shares by shipment volume (in MW), showing that designs based on wafers of silicon have dominated the market (mono-Si, multi-Si, and ribbon-Si, collectively referred to as crystalline silicon) since the beginning of the industry. Sales of thin-film modules rose during the 1980s when the first commercial-scale installations were financed, and again slightly in the late 2000s, because firms believed that the lower material cost facilitated through the thinner semiconductor would allow thin-film cells to become cheaper than crystalline silicon in the long run. However, both trends were relatively quickly reversed, so that since 1993 the share of crystalline silicon cells has never fallen below 80% of the global market share. Most commercial firms produce the dominant crystalline silicon design, and the technology can thus be considered in the *era of incremental change*.

For wind power the figure shows trends in the number of companies active in the market pursuing different design concepts. The graph illustrates that the 'Danish Design', featuring three-bladed, wind-facing, horizontally mounted rotors, has come to dominate the industry since the late 1980s, when the end of policies in California resulted in a massive shake-out of firms producing light-weight turbines (Menzel and Kammer, 2011). The *era of incremental change* began with the emergence of the dominant design around 1987, when more than 60% of firms produced the 'Danish design' and Danish firms held around 80% of the global market share (Garud and Karnøe, 2003). The Danish design is characterized by a rotor that (a) faces toward the incoming wind, (b) features three rotor blades and (c) operates with relatively low rotational speeds. The dominance of the Danish design has

only increased since then, albeit with different designs of the transmission system (notably variable-speed gearboxes and gearless transmissions).

a) Market growth



b) Design competition

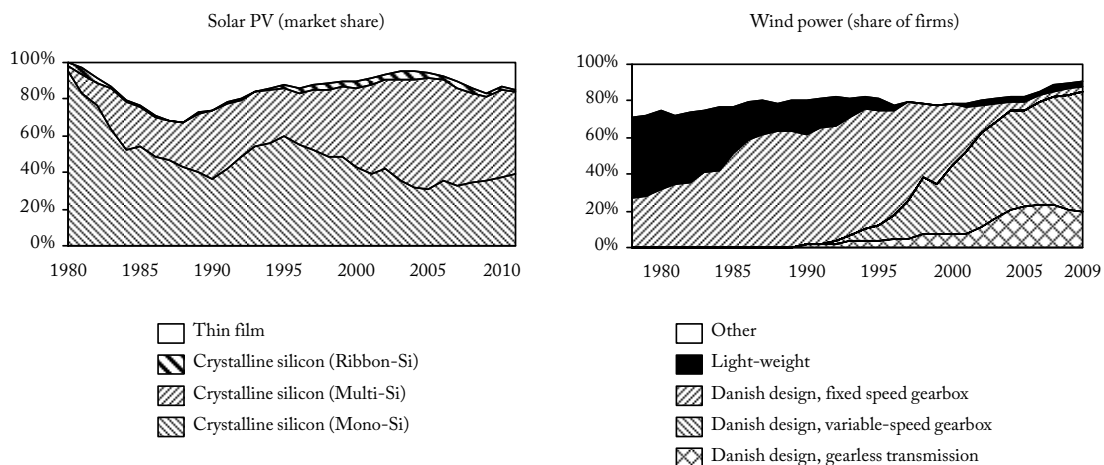


Figure 3: a) Annual installations of wind power systems (Peters, 2011, p. 132) and solar PV systems (IEA, 2012); b) Design competition in solar PV, as measured by market share of different designs (Fraunhofer ISE, 2012), and in wind power, as measured by the share of firms with different designs active in the market (Menzel and Kammer, 2011).³⁰

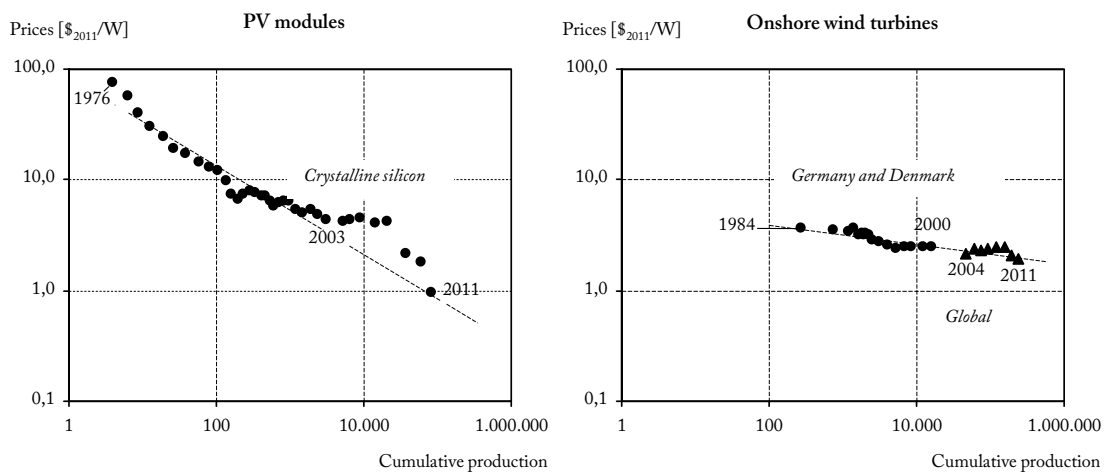
Technological change within the dominant designs has been cumulative and incremental over the last three decades, indicating an era of incremental change. Two prominent indicators of technological change in electricity technologies are investment cost³¹ for new installations (which reflect equipment prices) and efficiency. Both trends are shown in Figure 4a for *crystalline silicon PV modules* and *Danish-*

³⁰ The design data for the wind industry does not track design changes, i.e., firms are marked in the database with the design they entered the industry with. The displayed evolution therefore underestimates the rise of variable-speed turbine models, which was adopted by many firms who began with the Danish design. (Firms rarely switched between the other designs.)

³¹ Since fuel costs do not apply and operation and maintenance are comparatively low, investment costs dominate the economics of renewable electricity.

design wind turbines. Figure 4a shows ‘experience curves’, i.e., logarithmic unit prices over the logarithmic cumulative production. The data illustrate that initial prices came down gradually over the last decades. Cumulatively, the effects are very significant: For PV modules, prices in real terms decreased from 76\$ per Watt of electric capacity (\$/W) in 1976 to around 0.5-1 \$/W in 2012. The recent plateau and drop in prices is no indicator of a technological discontinuity; it was mainly driven by imbalances between supply and demand in the markets for raw silicon and solar modules (Candelise et al., 2013). The investment costs of wind farms decreased from around 3.6 \$/W to less than 2 \$/W in 2011 (BNEF, 2012a, 2012b). Here, too, deviations from the long-term price trend are driven more by factors other than technological change (Bolinger and Wiser, 2012).

a) Investment costs



b) Conversion efficiency

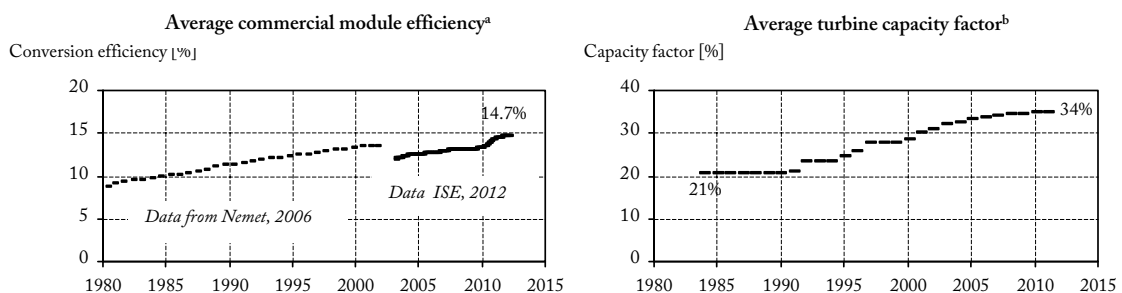


Figure 4: Technological change within the dominant designs in wind power and solar PV: a) Investment cost (BNEF, 2012a, 2012b); b) PV module conversion efficiency (Nemet, 2006; Fraunhofer ISE, 2012) and wind turbine capacity factors (BNEF, 2012b). Unlike conversion efficiency, the capacity factor includes improvements in siting. The break in the trends for cell efficiency is due to different data sources.

At the same time, suppliers were able to gradually increase the *technology quality* of the power generation equipment. Figure 4b compiles data for quality indicators commonly used by industry. For solar PV, it shows the average efficiency of commercial PV modules, which increased by a factor of around 1.7 since 1980. The increasing module efficiency reflects incremental reduction of losses in

many parts of the module and the cell, e.g., through improvements in cell materials, cell treatment, contact printing, contact materials, antireflective coatings, cell interconnection, etc. A similar increase – by a factor of 1.6 – can be seen in the average turbine capacity factors of newly built wind turbines, which relates the actual electricity generation to the maximum possible electricity generation per year. Capacity factors, too, reflect a range of incremental improvements, including the siting of turbines, larger turbine rotors, higher towers, variable-speed transmission systems, and improvements in control systems, thus yielding a comprehensive picture of qualitative progress in wind power. Patent applications grew exponentially in both technologies since the early 1990s, and now stand at several thousand per year (see Figure 5 below). This surge in patenting is consistent with typical patterns in the era of incremental change (Gort and Klepper, 1982; Lee and Berente, 2013).

4. Data and Methodology

4.1. Empirical Strategy

Section 3 provided evidence for the fact that both solar PV and wind power went through different stages of the technology life-cycle. However, the presented indicators offer little cues about the focus of innovative activity, and they leave unanswered whether the patterns conform to one or another model of the technology life-cycle.

This section introduces our patent-based methodology to study the technology life-cycles in wind power and solar PV. Patents have been used extensively to study trends in innovation in technological systems (e.g., Fleming and Sorenson, 2001; Rosenkopf and Nerkar, 2001), in part because they are readily available as large empirical datasets. However, large patent datasets make in-depth analyses difficult – such as the identification of product and process patents – while only containing a small number of patents with significant technological or commercial value (Griliches, 1990). Therefore, researchers have long been searching for ways to identify valuable patents, which can then be analyzed in more detail (Harhoff et al., 2003; van Zeebroeck, 2011).

Several studies in recent years have applied connectivity algorithms to the network formed by patents (as vertices) and patent citations (as arcs) in order to identify technologically significant patents (Choi and Park, 2009; Bekkers and Martinelli, 2012; Epicoco et al., 2014; Ho et al., 2014). The idea is that patent citations contain valuable information about knowledge ‘inheritance’ between patents and can thus be used to identify key linkages in technological evolution (Martinelli and Nomaler, 2014).

External validations show that this approach can reduce a large patent dataset down to a small selection of patents that were highly relevant for technological progress at the time of filing (Fontana et al., 2009; Barberá-Tomás et al., 2011). The sequence of these relevant patents is a representation of the core of the technological trajectory and gives insights into how the focus of innovative activity changed as the technology evolved over time (Verspagen, 2007; Martinelli, 2012; Epicoco, 2013). Huenteler et al. (2014b) further demonstrate that the topical focus of *patenting* along the technological trajectory also corresponds well to trends in *innovative* activity in the industry and that patent-citation networks therefore can be used to identify the emergence of dominant designs and technology life-cycle patterns. However, until now only few studies have combined this approach with a systematic representation of the technological system and classified the identified patents accordingly, as it has been done in detailed analyses of technological evolution in specific fields (e.g., Rosenkopf and Nerkar, 1999; Prencipe, 2000).

This paper integrates a citation-network analysis with a manual classification of the identified patents. *First*, the paper develops a patent and patent-citation dataset for solar PV and wind power for the period 1963-2009 (described in detail in section 4.2). *Second*, we apply two connectivity algorithms to this dataset to identify the core trajectory for both technologies (section 4.3). And *third*, we group the top 1,500 patents according to their technological focus – e.g., product design versus production process – to identify whether the technological trajectories match with either of the two representations of the technology life-cycle (section 4.4).

4.2. Patent Data

We compiled the database of patent and patent citation data with the objective to obtain a comprehensive dataset of global patenting in the two technologies over the time period 1963 to 2009.³² The patent data was extracted from the proprietary Derwent World Patent Index (DWPI) database, which collects data from 48 patent offices. We chose DWPI because it facilitated the assessment of patent content by providing expert-generated abstracts of all patents (see section 4.4), including translated abstracts for non-English entries in the database.

³² The search was conducted in 2013 but the database was truncated after 2009 to account for the time-lag between patent filing and publication.

The search string was developed through a two-step procedure. First, we compiled a list of relevant keywords extracted from the innovation literature (a total of 6 experts from the two industries provided feedback on the identified keywords). Then we iteratively curtailed the keyword list by applying it to the initial set of International Patent Classification (IPC) classes listed in the ‘Green Inventory’ of the World Intellectual Property Organization (such as the class ‘wind motors’ F03D) and manually checking random samples for irrelevant patents.³³ Second, additional IPC classes were added to the search string based on information on co-filings of relevant patents. Final tests indicated about 6% and 13% false positives as well as about 9% and 14% false negatives for wind power and solar PV, respectively.³⁴ Because connectivity algorithms are robust to false positives, we focused on reducing the error of exclusion when constructing the search filter – partly at the expense of the error of inclusion. Therefore, after retrieving the citation data of all patents (see below), we extended the database in a second iteration to include those 1,000 outside patents that received the most citations from the patents in the database (almost all of these were relevant solar and wind patents).

The citation data was extracted from the DWPI and Thompson Innovation databases, which together cover most of the patent offices’ data. We cleaned the citation data from duplicate citations between different patents in the patent families and excluded circular references.³⁵ One problem that arises when using citation data is that early patents have a disproportionately high likelihood of being getting cited because the population of potential citing patents is higher than for new patents. Therefore, in order to avoid a bias toward older patents, we discarded all citations with a lag between filings of citing and cited patent of more than five years. In a last step we removed all unconnected patents, i.e., all

³³ We applied the keywords to the titles, abstracts and claims of patents.

³⁴ To test for false positives, we randomly tested a total of about 1,000 patents for each technology (50 patents for each of the 18 and 20 four-digit IPC classes in the search strings for solar PV and wind, respectively). For false negatives, we checked how many of the patents filed by the top 12 pure-player PV manufacturers (by 2012 cell market share) and 8 pure-player wind turbine manufacturers (in 2010 by market share) were included in our database.

³⁵ Whenever we found circular references, i.e., mutual citations between patents, we deleted the citation coming from the patent with the earlier priority date. Such citations can occur when examiners add citations to new patents filed during the examination process, or when patents are filed in multiple countries.

patents without citation link to any other patent in the database. The final database contains 26,775 solar patent families³⁶ (55,687 linkages with a lag ≤ 5 years) and 8,907 wind patent families (18,718).

Given the time period represented in the database, our analysis is able to reliably identify technologically significant patents until at least 2005. Figure 5 shows how patents and citations are distributed over time. Both technologies saw a first increase in activity around 1980 and then an exponential increase in patenting from about 1995. Received and filed citations increase about proportionally to patent filings until 2005, after which received citations drop rapidly because patents after 2005 did not have a full five-year window of possible citing patents in the database.

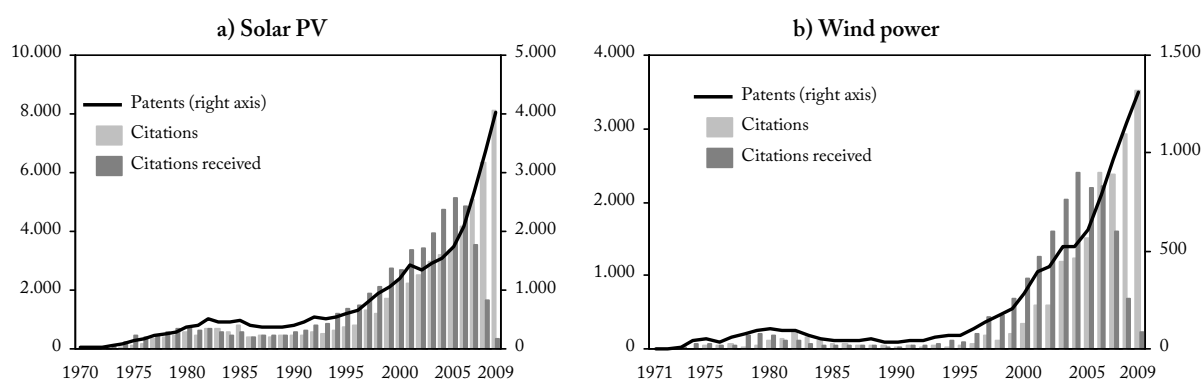


Figure 5: Descriptive statistics for patent filings, filed citations and received citations over time. Only citations with lag of ≤ 5 years are included. The trends in patenting are in line with other studies who find a surge in patenting activity in the era of incremental change (Gort and Klepper, 1982; Lee and Berente, 2013).

4.3. Connectivity Analysis

In order to identify differences in the development of solar PV and wind power we applied connectivity algorithms to the patent data. We designed the analysis in order to address two aspects of the broader research question: *In step I*, we identified the current trajectory of innovative activity and traced back the technological foundations of this current trajectory. The results of this step are used to characterize the current stage of the technological lifecycle in the two technologies (i.e., at the end of the observed period in 2009) and can yield insights into where the technology is heading at the moment. *In step II*, we analyzed how and when the current trajectory emerged as the industry's dominant trajectory and which alternative paths of development existed in the past (and were

³⁶ We used patent families instead of individual patents to avoid double-counting of multiple filings in different offices.

abandoned). The results of this step are used to characterize the technology life-cycle as a whole, including significant shifts in the focus of innovative activity in the past. For both analyses, we used connectivity algorithms to extract sub-networks small enough to be categorized manually (see Section 4.4).

Both analyses employ the *search path link count* (SPLC) algorithm and the *critical path method* (CPM). The SPLC algorithm aims to identify the most important arcs (i.e., citations) in the network (Hummon and Doreian, 1989; Verspagen, 2007). A ‘search path’ is every possible way from a sink in the network (i.e., a patent that only *cites* and does not get cited) to a source (patents that only *get* cited). The ‘link count’ enumerates all possible search paths in the network, and counts how often an arc lies on such a search path. The count is then assigned as weight to each adjacent patent, thus identifying patents along the most important technological linkages in the network. Because the weight of patents in the network is highly skewed, with a few patents holding most of the aggregate weight, this algorithm can be used to reduce the complexity of the network significantly – e.g., in the case of wind power 158 of the 8,907 connected patents hold between them 80% of the total weight (494 patents hold 95%). Building on the results of the SPLC, the CPM determines the search path with the largest total sum of arc weights (e.g., Fontana et al., 2009; Epicoco et al., 2014). We implemented the algorithms using Pajek (de Nooy et al., 2011).

To *characterize the current stage of the technological lifecycle* (step I), we applied the SPLC and the CPM to the full network 1963-2009 for each technology (networks B in Table 3 below) to identify the core trajectory or ‘backbone’ of the trajectory (sub-networks C in Table 3) (Epicoco, 2013; Prabhakaran et al., 2014). As a robustness test we also extracted and analyzed the top 80% and top 95%-weight networks (applying a so-called ‘vertex-cut’ algorithm; D and E) (Batagelj and Mrvar, 2004). This first step reveals the most important patents and citation linkages in the full network – i.e., the current dominant trajectory and its technological roots. However, it does not reveal when the current trajectory was selected or what the alternatives were. Because the algorithm uses *all* information contained in the network to evaluate *each* patent, the evaluation of patents filed in year t change over time as new patents are filed in $t+1$, $t+2$, etc. This means that previously important trajectories that turned out to be dead-ends are no longer visible. Therefore, step II is necessary to analyze the technology life-cycle in ‘real time’.

To *characterize the technology life-cycle as a whole* (step II), we applied the CPM to a series of 35 gradually growing networks N_t , starting with a network N_{1975} covering the years 1963-1975³⁷ and ending with the full network N_{2009} covering 1963-2009 (displayed in Figure 10 are 8 of them, in 5-year steps). We then merged the critical paths into one network and color-coded each node by the last network N_t in which it is part of the critical path (sub-networks F in Table 3). This analysis reveals dead-ends and abandoned trajectories hidden in the data. Descriptive statistics of the full networks and all sub-networks are provided in Table 3 below.

Table 3: Descriptive statistics of patent data.

	A	B	C	D	E	F
Technology	Full network (all linkages)	Full network (linkages with lag \leq 5 years)	Critical path (linkages with lag \leq 5 years)	80%-weight network (linkages with lag \leq 5 years)	95%-weight network (linkages with lag \leq 5 years)	Sequential critical paths (linkages with lag \leq 5 years)
Time period	1963-2009	1963-2009	1963-2009	1963-2009	1963-2009	1963-1975 ... 1963-2009
Solar PV	32,919 (129,993)	26,775 (55,687)	35 (53)	322 (1,063)	915 (2,069)	3 (2) ... 35 (53)
Wind power	11,330 (41,268)	8,907 (18,718)	36 (60)	158 (499)	494 (1,827)	4 (3) ... 36 (60)

4.4. Patent-Content Analysis

As a final step, we manually coded the abstracts and claims of the patents in the sub-networks C-F extracted in step 3 in order to identify the focus of innovation over the technology life-cycle.

The classification of the patent abstracts was done according to the coding schemes shown in Table 4 (solar PV) and Table 5 (wind power). For each of the two technologies, we differentiated 5 functional elements of the system: The system level (i.e., inventions that claimed entire PV system or wind turbine designs) and four different sub-systems each: in the case of PV systems, we classified patents relating to (1) cells, (2) modules, (3) mounting & tracking systems and (4) grid connections patents; in

³⁷ The year 1975 was chosen as a starting point because at that time the cumulative number of patents exceeded 100 for both technologies (257 for PV, 111 for wind).

wind turbines, we classified patents relating to (1) rotors, (2) power trains, (3) mounting & encapsulation systems and (4) grid connections. In addition, we classified within each sub-system category (e.g., cells, rotors) whether the patent refers to product innovations or process innovations. Table 4 and Table 5 give examples for each of the resulting 9 classes of patents per technology.

One mechanical engineer and one electrical engineer independently classified each of the patents according to the abstracts' focus in the technological system. Overall the agreement between the two coders was 87%. In cases of disagreement a consensus was reached after discussing the patent content in detail.

As a last step, we discussed our results for the focus of innovative activity over time with academic experts on the solar PV (5 experts) and wind power industries (4). All nine confirmed the trends displayed in the data.

Table 4: Coding scheme for patents in solar PV.

Content code	Content	Example
PV system	Novel PV system design in which novelty has to do with the design of at least two of two sub-systems (cell, module, mounting system and grid connection)	Tubular photovoltaic solar cells situated at the focus of a line-generated parabolic reflector (US 3,990,914)
Cell	<i>Product</i> Novel design of cell or cell materials	Layered photovoltaic cell with more than one active junction for higher efficiency (US 4,017,332)
	<i>Process</i> Novel production process for cell or cell materials	Production process for crystalline thin-film cell (US 5,130,103)
Module	<i>Product</i> Novel design of module, including cell separation, cell interconnection or cell encapsulation, including specific materials and components	Amorphous silicon solar cell element encapsulated by a filler with low moisture permeability (US 5,344,498)
	<i>Process</i> Novel production process for module, module materials or module components	Solar cell module manufacturing method with improved sealing characteristics (US 20,040,191,422)
Mounting system	<i>Product</i> Novel design of array, mounting system or tracking system (including control system)	Modular PV mounting system with batten-and-seam type interconnection that can be attached to roof (US 5,232,518)
	<i>Process</i> Novel production or installation process for array, mounting system or tracking system	Method to install rooftop solar system (US 20,010,034,982)
Grid connection	<i>Product</i> Novel design of inverter, cabling, storage or control system (incl. grid integration control system)	Circuitry design for PV system with earth leakage circuit breaker (US 6,107,560)
	<i>Process</i> Novel manufacturing or installation method for inverter, cabling, storage or control system	Inverter manufacturing method (JP 4,915,907)

Table 5: Coding scheme for patents in wind power.

Content code	Content	Example	
Wind turbine system	Novel wind-turbine design in which novelty has to do with the design of at least two sub-systems (rotor, power train, mounting & encapsulation, and/or grid connection)	Vertical axis turbine with novel rotor and novel drive-train arrangement (US 3,902,072) or horizontal-axis rotor with rotor-integrated generator (US 4,289,970)	
Rotor	<i>Product</i>	Novel design of rotor or rotor components (incl. rotor control system)	Rotor arrangement with teetering hub and rotor control mechanism (US 4,201,514)
	<i>Process</i>	Novel manufacturing or installation method for rotor or rotor components	Rotor blade manufacturing method (JP 4,641,366)
Power train	<i>Product</i>	Novel design of power train or power train components (incl. power train control system)	Compact, gearless power train (US 6,921,243)
	<i>Process</i>	Novel manufacturing or installation method for power train or power train components	Manufacturing method for magnets of multi-polar generator (EP 2,389,512)
Mounting & encapsulation	<i>Product</i>	Novel design of nacelle, tower or foundation (incl. climate and vibration control system)	Tower-nacelle arrangement in which transformer is mounted inside the top of the tower (US 7,119,453)
	<i>Process</i>	Novel manufacturing or installation method for nacelle, tower or foundation	Installation method for offshore wind turbine tower (GB 2,460,172)
Grid connection	<i>Product</i>	Novel design of transformer, substation, cabling or wind farm integration (incl. grid integration control system)	Electrical connection of wind turbines in a wind farm, including substation and individual transformers and cabling (US 7,071,579)
	<i>Process</i>	Novel manufacturing or installation method for transformer, substation or cabling	Method of mounting power cables (ES 2,283,192)

5. Results

This results section is structured in line with the sequence of analyses presented in the methodology section. We start by characterizing the current stage of the technology life-cycle of the two technologies (section 5.1; analysis step I of the connectivity analysis). Then we characterize the technology life-cycle as a whole, including significant shifts in the focus of innovative activity in the past (section 5.2; analysis step II). The results reveal strongly contrasting development paths in the two industries. In the development of solar PV technology early product innovations were soon followed by a series of interlinked product and process innovations. In the current stage of the life-cycle, most innovative activity focuses on the cell production processes. In wind turbine technology, in contrast, the focus of innovative activity shifted over time through different parts of the product, rather than from product to process innovations, and is now on incremental product improvements in interdependent sub-systems and components. The consequences of these striking differences for policy makers are discussed in section 6.

5.1. Characterizing the Current Life-Cycle Stage

The core trajectories in the full networks of solar PV and wind power (Figure 6a and b) allow us to characterize the current stage of the life-cycle, including the technological foundations of current innovative activity. Two main differences between the technologies stand out. *First*, the breadth of innovative activity is remarkably different: the critical path in PV remains focused on the cell, with only two module patents as exceptions, whereas innovative activity in wind power is spread much more evenly across the four sub-systems: 8, 10, 15 and 3 patents in the rotor, power train, grid connection and mounting & encapsulation, respectively. Additionally, the path in the wind network shows a sequential pattern, focusing first on the rotor (which can be seen as core sub-system), until 1987, before shifting to the power train (mid-1980s to mid-2000s), grid-connection issues (from late 1990s) and mounting & encapsulation structures (since the early 2000s). *Second*, the two technologies differ in the *type of innovation* along the trajectory, in particular the relative emphasis on product and process innovations. As can be seen from the color coding in Figure 6a, the current innovative activity in solar PV is almost exclusively focused on the cell production process. Indeed, 25 of the last 26 nodes on the critical path, covering the period 1987–2009, are cell process innovations. Only the first 9 patents and one later patent (in 2004) on the critical path are product innovations. The wind network in Figure 6b, in contrast, shows virtually the opposite: There is not a single process-related patent on the critical path; in fact only 3 of the top 494 patents representing the top 95% of the vertex weight (network E) relate to the production or installation process. More detail on the patents on the critical paths is presented in Table A3 and Table A4 in the appendix.

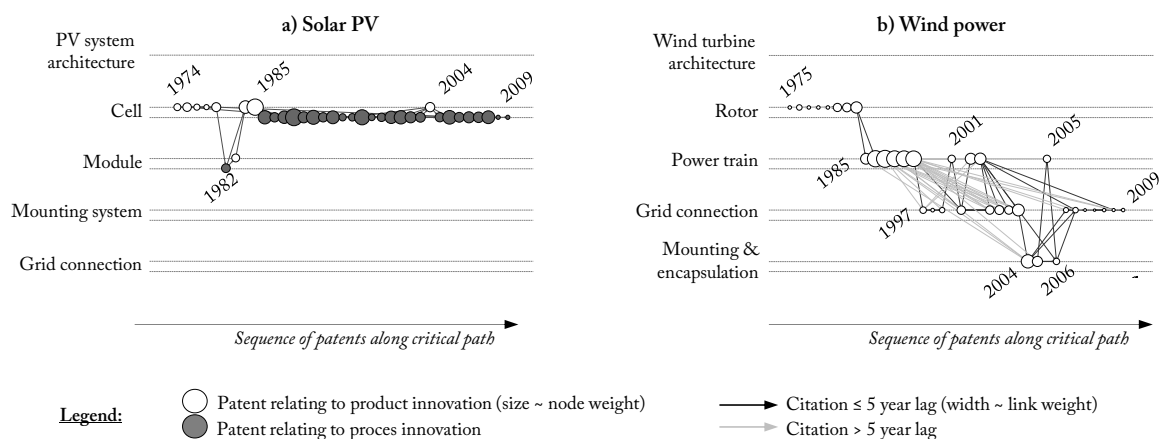


Figure 6: Critical path in full networks (network C in Table 3) showing the currently dominant trajectory of innovative activity.

The patterns observed in Figure 6 allow to draw conclusions about the innovation process in the era of incremental change in the two technologies: in solar PV, the current trajectory of innovative activity is dominated by cell process innovations, which draw relatively little on knowledge developed for other parts of the system (such as mounting structures or grid integration routines). In contrast, the current trajectory of innovative activity in wind power is centered on product innovations. The last patents on the critical path focus on vibration control in the tower. These product innovations draw not only on knowledge from the sub-system in question but are based also on innovations in other parts of the system, as can be seen from the citations that cross sub-system boundaries (citations with a lag of more than 5 years were not included when analyzing the connectivity, but are nonetheless shown in Figure 6 to illustrate the multitude of linkages between patents in wind power). This points toward the complexity of the product architecture and the ‘systemic’ nature of innovation in wind power.

The two observations from the critical paths remain valid when looking at quantitative indicators describing the broader trajectory, shown in Figure 7. (These analyses are based on the 80%-weight networks D, which are also shown as graphs in Figure A1 in the appendix). Figure 7a and b show comparable data for the *breadth* of innovative activity, represented by the share of innovative activity in different parts of the system for solar PV and wind power. The graphs illustrate that the focus on the cell sub-systems remains more or less unchanged (cell innovations represent between 60% and 90% of the weighted activity for most of the observed period). Opposed to that, the focus in wind turbine technology is *sequential* and shifts through different parts of the system in a way that each sub-component has a share of at least 40% of the weighted activity in different time periods. The *type of innovation* can be compared in Figure 8a and b. In solar PV the focus shifts over time from product innovations, which represent an average of 64% of the weight between 1972 and 1985, to process innovations with an average 73% of the weight in 1990-2009. The focus of innovative activity in wind power did not shift to process innovations (of which there are none in the 80%-weight network), but to *systemic patents*, as shown in Figure 8b. Systemic patents are defined here as patents that received more than half of their citations from patents in other sub-systems (the 7 system-level patents were excluded from this analysis). Their share increased from 25% in 1975-1979 to 63% in 1990-94 and 58% in 2005-09. This, again, illustrates the systemic nature of innovation in wind power, as did the patterns of citations seen in Figure 6b.

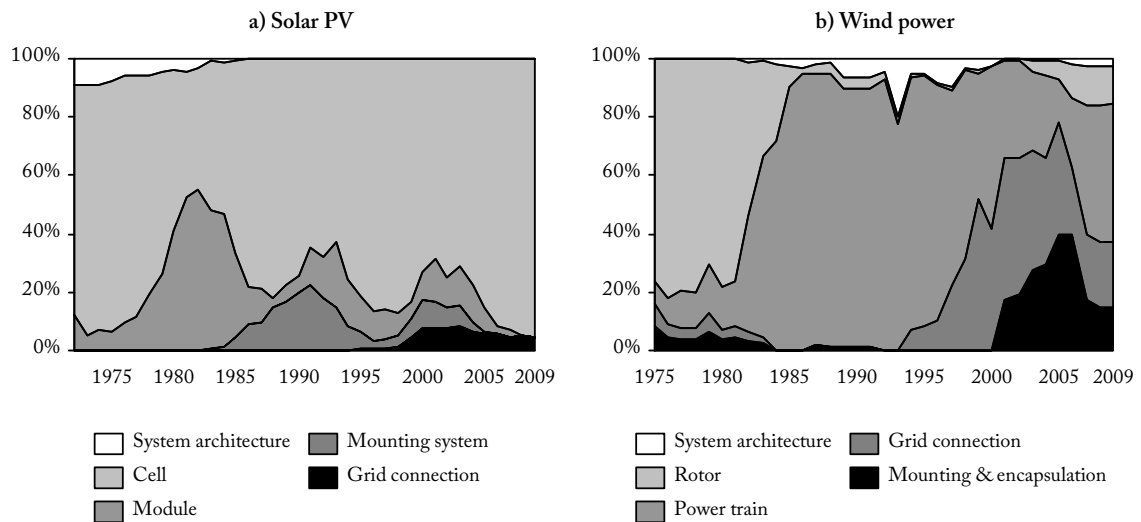


Figure 7: Share of innovative activity in different parts of the technological system (based on patent-content categorization of 80%-weight networks D).

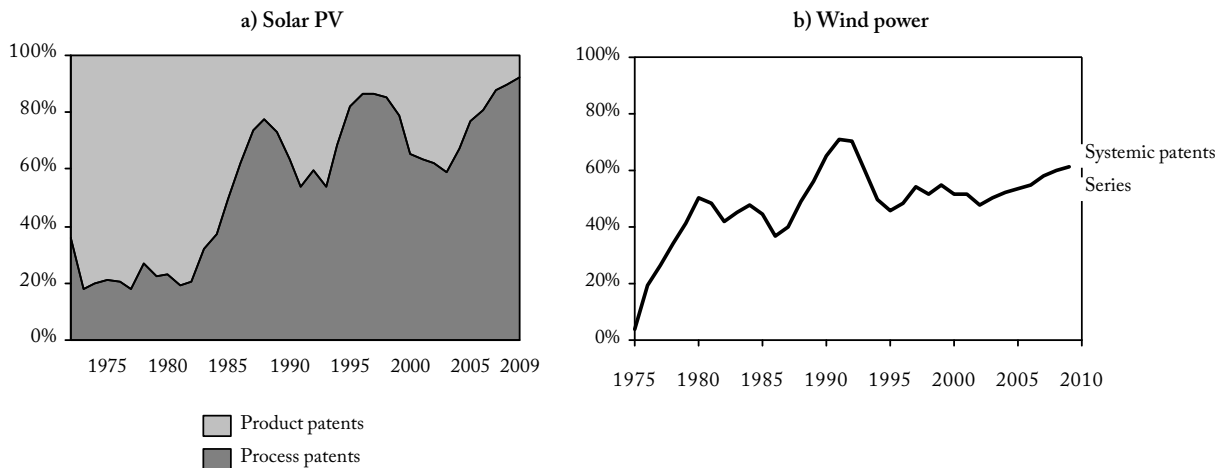


Figure 8: a) Shift from product to process innovation along life-cycle in solar PV, b) Share of 'systemic patents' in wind power over time, defined as patents that received more (>50%) citations from patents in other sub-systems than from its 'own' sub-system (system-level patents were excluded from this analysis).

5.2. Characterizing Previous Stages of the Technology Life-Cycle

As discussed in section 4.3, the results presented so far allow us to characterize the current stage of the technology life-cycle, but they offer only limited information on shifts in the patterns of innovation in the two technologies in the past. The observation that the later stage of the life-cycle in PV is focused on cell process innovations does not mean that module or grid connection innovations were never important. This section reports results that aim to identify and characterize these past life-cycle stages. The algorithms are the same as those used for the analyses in section 5.1, but were applied not to the full network but to a series of gradually growing networks N_t (where t is the year up to which patents are included in the network).

The results for the series of networks yield a detailed picture of how the current trajectories in the two technologies *emerged over time*, and which alternative trajectories were abandoned. The first main set of observations is contained in Figure 9, which shows the gradual stabilization of the critical paths in the two networks. Specifically, the figure presents a ‘hazard rate’, which is a measure of variation of the core trajectory, for patents on the critical paths of the gradually growing networks (Huenteler et al., 2014b). This hazard rate is to be interpreted as follows: for each year t (on the x-axis), the graph shows how many patents on the critical path of N_t are *no longer* on the critical path when five years of additional patent data are added to the network – i.e., on the critical path of N_{t+5} . The decline of the hazard rate in both technologies means that the critical path gradually stabilized over time, although with a major discontinuity in solar PV around 1995 (more below). One can derive from these graphs an approximation of the time when the period of major competition between alternative trajectories ended. This provides insights about the technology life-cycle as a whole, and specifically about the emergence of a dominant design: If one defines a trajectory as stable as soon as it conserves at least 50% of the patents on the critical path over a period of five years (i.e., the hazard rate remains below 50%), a stable technological trajectory emerged in PV in 1996 and in wind power in 1984 (or 1989, when the value is exactly 50%). These dates roughly match with the data on design competition in the market presented in Figure 3 as well as with qualitative accounts of the emergence of dominant designs in the two technologies (Menanteau, 2000; Bergek and Jacobsson, 2003; Nemet, 2009).

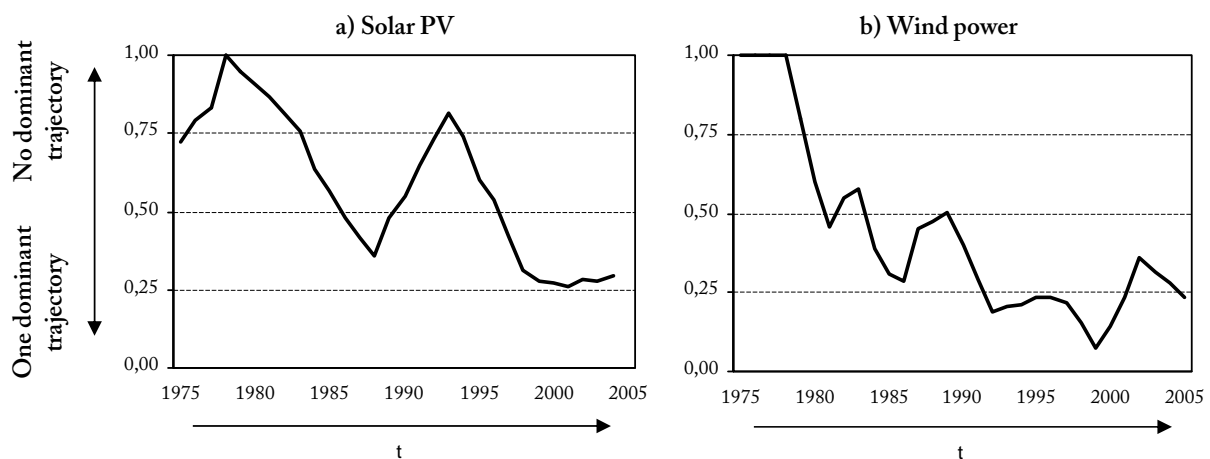


Figure 9: Hazard rates of patents on the critical path, indicating share of patent that is still on critical path after five years of new patent filings have been added to the network.

The second set of more detailed observations is contained in Figure 10, which integrates the critical paths of 8 different networks (N_{1975} , N_{1980} , N_{1985} ... N_{2009}) in one graph.³⁸ Each patent in the graph is colored with a different shade of grey, which indicates the year of the last critical path the patent is part of. This figure allows us to identify two aspects of the earlier stages of the technology life-cycle. *First*, it shows how the focus of innovative activity in the two technologies evolved in ‘real time’, because unlike in Figure 6 the evaluation of earlier patents is not influenced by the (ex-post) information which trajectory eventually ‘succeeded’. When comparing the graphs to those shown in Figure 6 above, it becomes clear that competing trajectories, indicated by the gray shades and the non-white patents in the graph, existed in PV mainly until around 1995. In wind power the currently dominant trajectory had already emerged by the late 1970s – only a few non-white patents are located on alternative trajectories that branch off here and there in the late 1970s and mid-1980s. In terms of solar PV, the graph suggests that the industry already focused strongly on production processes in early stages. However, opposed to what can be observed when looking at the currently dominant trajectory in Figure 6a, there was also a period (until 1995, and then again briefly in 2002-03) when *module* product and process innovations were very important. In wind power, the graph demonstrates that the current trajectory has been dominant for so long (compare Figure 9) that the additional critical paths add little information to the analysis of the focus of innovative activity. Additionally, it is noteworthy that not a single patent on any of the eight critical paths has been on the process level which reinforces the observation made from Figure 6b.

Second, Figure 10 allows us to identify trajectories that had been important but are now out of focus. The graph contains three such trajectories in each of the two technologies. In solar PV, all three exhibit a stronger focus on the module subsystem than the current trajectory. The first two trajectories, which end in 1980 and 1995 and are marked (a) and (b) in the graph, both show a pattern of close linkage between product and process innovations. The first set of these, marked (a), focuses on ways to encapsulate solar cells in laminates that are radiation-transparent and protect the cells from water and other environmental influences (e.g., US 4,067,764, US 4,009,054, US 4,224,081). These innovations

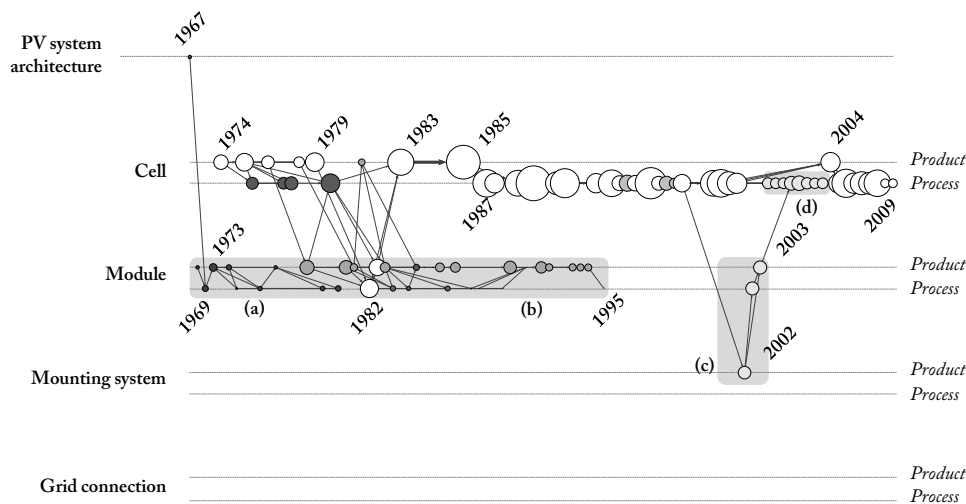
³⁸ To test the robustness of this approach, we compared the network combining the 8 critical paths (network ‘I’) to one that combines all patents that are on at least three critical paths (‘II’). In solar PV, all 65 patents of II are also part of I, which contains 92 patents. In wind power, II contains 50 patents, 38 of which are part of I, which has 47 patents; those that are not on I are patents from the late 1970s and early 1980s on the system level and in the sub-system rotor, thus adding little information to Figure 10.

are technologically independent of the current trajectory but are nonetheless still important parts of current modules. The second set of patents (b), which spans a period from the late 1970s to the mid-1990s, relates to the electrical integration of *thin-film modules* (e.g., US 4,315,096, US 4,624,045 and US 4,650,524), a technology that was long regarded as the most promising technology but which is now increasingly marginalized (see Figure 3 above). In thin-film solar PV, the process of module and cell manufacturing is much more integrated than in crystalline silicon PV, which is reflected in the stronger focus on module patents on this trajectory.³⁹ The closer integration of product and process innovations in thin-film PV, too, reflects characteristics of the technology, for two reasons. On the one hand, there are a lot more design variations possible due to a larger choice of possible materials. On the other hand, the economic and technological feasibility of alternative thin-film cell designs and materials hinges almost entirely on the production process, because the production process (i) is even more automated than that of crystalline-silicon cells and (ii) does not allow using production equipment from the chip industry.⁴⁰ This close relationship suggests that the predominant focus on cells and the production process might today be slightly different if thin-film modules had emerged as dominant trajectory. A third, more recent abandoned trajectory contains patents relating to encapsulation and mounting elements (c) as well as patents relating to the production of specific materials for thin-film cells (d). The latter suggest that renewed focus on thin-film cells in the mid- to late 2000s in some parts of the industry (cf., Figure 3) is also reflected in the patent network.

³⁹ Thin-film modules are produced by depositing a thin film of semiconductor material on a large surface, cutting individual cells into the large surface and then connecting these cells electronically. That means cell and module manufacturing are part of one integrated production process, which is why they are almost never physically or organizationally separated. In crystalline silicon, in contrast, cells are produced on small surfaces first and then integrated into a module.

⁴⁰ See, e.g., Jager-Waldau (2004). Indeed, manufacturers of thin-film modules had and still have much more problems to translate the high-efficiencies and high-yields of smaller, laboratory-constructed cells to production volumes (e.g., Razykov et al., 2011).

a) Solar PV



b) Wind power

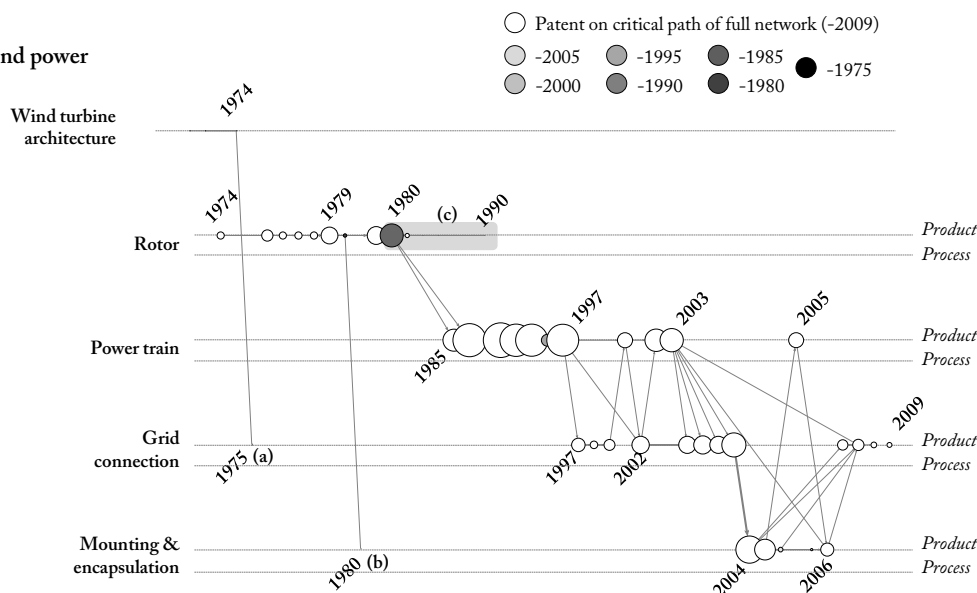


Figure 10: Network for solar PV and wind power which combine patents from the 8 critical paths of networks N_{1975} , N_{1980} , N_{1985} , ..., N_{2009} to illustrate competing trajectories and emergence of currently dominant trajectory. The color of each patent (node) indicate the year of the last critical path that the patent is part of. The letters (a)-(c) in solar PV and (a)-(b) in wind power indicate ‘abandoned’ trajectories.

The wind power graph shows three alternative trajectories that branch off early on and are representative of alternative technological paths pursued in the early days of the wind industry. The first one, marked (a), is representative of a few early critical paths that focus on alternative, vertical-axis rotor designs (e.g., US 3,883,750, US 4,012,163, US 4,115,027), a technological path that was pursued in the 1970s and 80s but then quickly abandoned outside of small niche applications. Connected to this is the option to store electricity in a flywheel, which can be linked to vertical axes turbines more easily than to current turbines (US 4,171,491, US 3,944,840, US 4,035,658). The one marked (b) branches off to an early patent claiming a mechanical mechanism to control vibrations induced by the

reorientation of a horizontal rotor to changing wind directions (US 4,692,094; also US 4,557,666). In the late 1980s several further critical path patents are linked to alternative, mechanical mechanisms to control the rotational speed of a rotor of a horizontal axis turbine (e.g., US 5,096,378, US 4,692,095), such as the one trajectory marked by (c) in Figure 10 which branches off to a mechanical rotor control system (using a spring and a rotating mass which adjusts the orientation of each blade to the wind to avoid over-speeding). These represent alternatives to electronic control systems, which is now standard throughout the industry.

6. Discussion

Our results suggest that solar PV and wind power followed very different technology life-cycles over the last four decades, but that both patterns can be explained with existing theoretical models. Linking the temporal patterns in solar PV and wind power to the theoretical models allows us to draw conclusions from the literature about the learning and innovation processes in the two technologies. The models point toward very different innovation and learning processes in the two technologies – differences that are likely to be even wider when looking at the entire technology space in the energy sector, as discussed in section 6.1. The different innovation and learning processes imply the need to tailor technology policy to technological characteristics (6.2). The findings further help conceptualizing previously inconclusive evidence about the impact of technology policies in the past (6.3).

6.1. Technology Life-Cycles in Energy Technologies

Our results demonstrate that the technology life-cycle of solar PV conforms well to the predictions of the A-U model of mass-produced goods: early product innovations were followed by a surge of process innovations in solar cell production. Wind power, on the other hand, went through a life-cycle that closely resembles the predictions from the Davies model for the life-cycle of complex-products and systems: after an initial period with competing product architectures, the focus of innovative activity shifted over time through different parts of the product, rather than from product to process innovations.

As discussed in section 3.1, the two technologies differ in the two main determinants of these patterns, the complexity of the product architecture and the scale of the production process. However, they are by far not the most extreme cases within the energy sector. When going beyond the technologies

analyzed in this paper, it quickly becomes clear that the dichotomy of ‘complex products and systems’ and ‘mass produced technologies’ alone does not suffice to describe the full variety of energy technologies. Figure 17 locates a broader set of energy technologies in the technology space generated by the two characteristics. Complex products and systems can be further divided into *infrastructure systems*, such as public transport systems and electricity grids, and *design-intensive products*, which include most large electric power plants. Infrastructure systems are highly complex and provided through a project-based production process, and thus involve hardly any process innovation. Design-intensive products are manufactured in small but significant quantities and thus involve some form of process innovation. On the other end of the spectrum, mass-produced goods are divided into *continuous-flow processes* (such as the production of transport fuels), for which the process is the primary focus of innovation from beginning, and *process-intensive products*, which involve some experimentation with different product designs in the beginning (solar PV, fuel cells). The graphic also shows two groups of technologies that do not fit on the continuum between mass-produced goods and complex products and systems: (i) *low-tech products* (small wind, small hydro turbines) which are relatively simple and produced in very small batches, and have potential for neither significant product nor process innovation, and (ii) *mass-produced complex products* (electric cars, grid-scale batteries), which involve continued product and process innovations over the entire technology life-cycle.

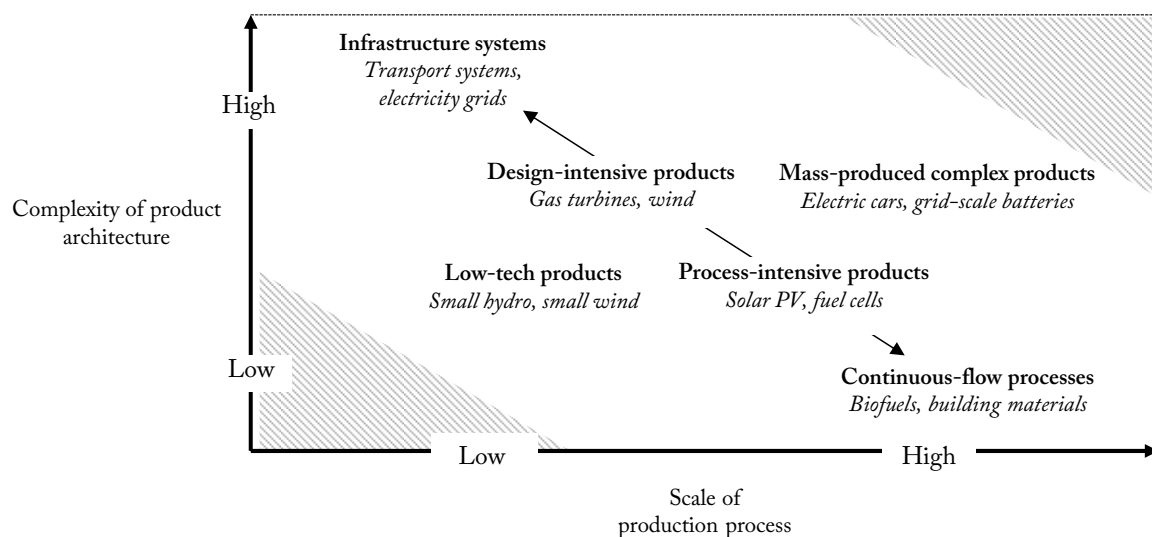


Figure 11: Stylized classification of different energy technologies according to scale of production process and complexity of product architecture.

When comparing the case technologies with those listed in Figure 11, it becomes clear that solar PV and wind power are in fact relatively similar. Wind turbines can be positioned in the lower right corner of complex products and systems, which implies that the systemic nature of innovation will be even

more pronounced in these cases than observed in wind power, so will the need for learning-by-using and user-producer interaction. Solar PV systems can be positioned in the upper left corner of mass-produced goods, some of which will thus be even more pronounced in the focus on process innovations, which also implies more pronounced economies of scale and learning-by-doing potentials. The technologies that are located to the left or right of the diagonal in Figure 11 are more difficult to characterize. Deducting from the patterns observed for the technologies *on* the diagonal, low-tech products can be expected to have relatively little absolute potential for learning and cost reductions; mass-produced complex products, on the other hand, can be expected to exhibit large potentials in both areas of learning and economies of scale.

6.2. Implications for Technology Policy

The life-cycle patterns identified in this paper point toward very different sources of relevant experience and potentials for innovation in the two analyzed technologies and the energy technology space in general. This section explores the implications of these differences for technology policy. A particular focus is on the design of so-called ‘deployment policies’, because in recent years, rather than focusing purely on public investment in R&D, many countries provide public resources for the deployment of clean technologies in order to induce innovations and ‘buy-down’ cost (e.g., PCAST, 1999; Gallagher, 2014).⁴¹ Much of the policy debate on the function of such deployment policies in the innovation process is centered on *learning-by-doing* in manufacturing and *economies of scale*, reflecting the A-U technology life-cycle model. However, our analysis shows that the energy sector comprises technologies that do not conform to this model of the technology life-cycle.

Deployment policies typically target relatively mature technologies. The two contrasting models of the technology life-cycle discussed in section 2.1 suggest that technological trajectories in the energy sector differ in three aspects that affect the role of deployment – and thus, the potential role of deployment policies – in the innovation process in later stages of the technology life-cycle: *First*, economies of scale in manufacturing, and thus *the absolute size of the supported market*, are much more important for mass-produced goods than for complex products and systems. Mass-produced goods need the prospect of a large market to realize economies of scale in manufacturing and to justify investments into R&D for

⁴¹Overall, the International Energy Agency estimates that the world will spend up \$1.2trn on wind power and \$1.1trn on solar PV over the next 25 years (IEA, 2014).

specialized production equipment and materials. If the prospect of such a market is too uncertain, a ‘chicken-and-egg’ situation can arise in which the market does not grow because cost are too high and cost cannot come down because the market is too small (e.g., Cantono and Silverberg, 2009). In complex products and systems, where most production facilities remain general-purpose, other variables besides market size are more important for the empirical relationship between deployment policies and innovations or cost reductions. *Second*, by facilitating feedback cycles between R&D and technology users, deployment can play a significant role in reducing technological uncertainty in complex products and systems, where uncertainty about product performance and user needs remain high throughout the technology life-cycle. While existent, the benefits from additional long-term and large-scale testing for the R&D process can be expected to be much smaller in mass-product products. *Third*, because user-producer interaction is so important, geographical and organizational proximity of markets and users can be very important for the R&D and innovation process in complex products and systems. In contrast, proximity appears much less relevant for mass-produced goods.

These three characteristics can serve as guideposts for technology policies that aim to make use of deployment to stimulate innovation (see Figure 12 and Table 6). For mass-produced goods, large markets, ideally coordinated internationally, are needed to enable the necessary economies of scale and the learning-by-doing in production. At the same time, policy support needs to make sure that cost competition remains high, e.g., by auctioning off subsidies, by dynamically adjusting incentives or by requiring supported firms to publish cost data. For larger and more complex technologies such as wind turbines, geothermal systems, nuclear power plants, and tidal energy systems, deployment policies have to go beyond simply subsidizing scale to in order to fully realize their potential innovation impact. For these technologies, deployment policies need to be understood as R&D policies rather than merely as subsidies. Rather than enabling economies of scale, deployment policies should be targeted at creating ‘performance-driven’ niche markets (Grubler and Wilson, 2014): they should not aim for very large roll-out of existing technologies, but be explicitly be targeted at reducing technological uncertainty, for example by providing grants to innovative product features, tying subsidies to requirements to publish cost and performance data, or by financing experimentation in different geographical and climatic environments. Furthermore, deployment policies could be accompanied by measures to enhance user-producer interaction (e.g., technology platforms or grants for consortia), improve market transparency (through collecting and publishing performance data) and gradually adjust performance standards (e.g., as it has been done with grid-integration requirements for wind turbines).

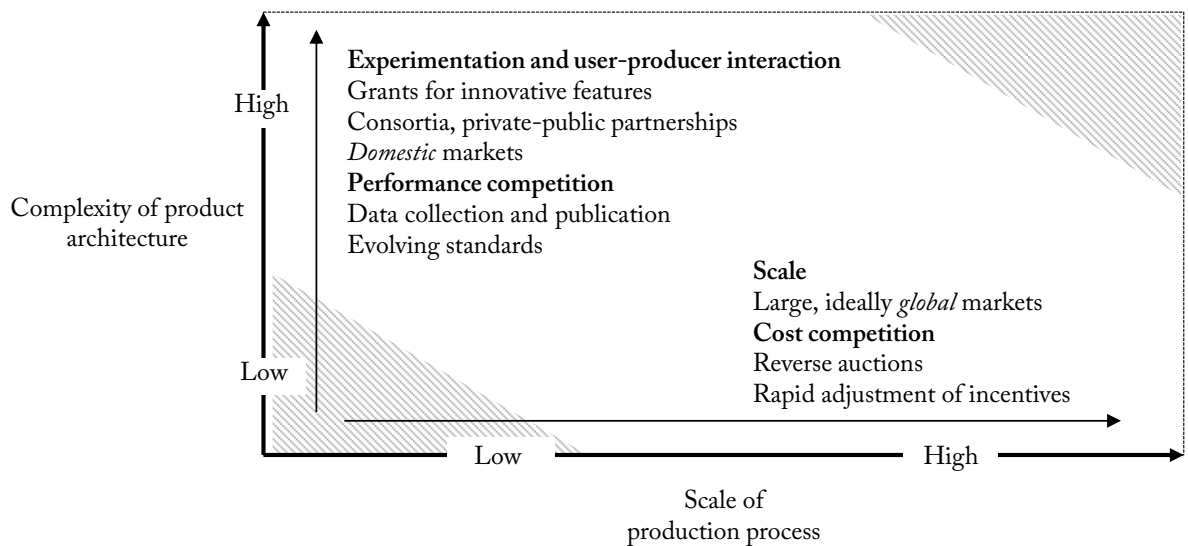


Figure 12: Characteristics of deployment policies if tailored to the characteristics of the two life-cycle models.

	Mass-produced energy technologies	Complex energy technologies
Primary objective	Enabling economies of scale & learning by doing in commercial-scale production processes, enable manufacturer-supplier interaction	Enable full-scale experimentation in use-environment, reduce uncertainty about product innovations, enable user-producer interaction
Geographical scope	Large-scale (ideally global)	Close to producers
Primary actors in innovation process	Manufacturers & their suppliers (materials, production equipment)	Users, manufacturers and component suppliers
Creating pressure to innovate	Cost competition drives innovation -> governments need to continuously adapt remuneration, minimize entry barriers and standardize regulation across jurisdictions	Evolving requirements and technological opportunities drive innovation -> incentivize continuous experimentation; create transparency about performance characteristics; monitor and continuously adapt performance requirements
Complementary policies	Rapid adjustment of incentives, reverse auctions	Grants for innovative features; consortia; private-public partnerships

Table 6: Characteristics of deployment policies tailored to the characteristics of the two life-cycle models.

6.3. Reconciling Empirical Evidence

Our analysis provides quantitative evidence for systematic differences between solar PV and wind power. This evidence helps reconciling two areas of conflicting evidence about the impact of technology policies on innovation.

First, there is an ongoing academic debate about whether subsidies for technology deployment can stimulate innovation and technological learning, or just enable firms to exploit existing designs and economies of scale (Nemet, 2006, 2009; Hoppmann et al., 2013). The life-cycle models that match our findings for the two technologies suggest that the effect depends on characteristics of the supported technology. Indeed, deployment subsidies in solar PV primarily enabled innovations in

manufacturing (Norberg-Bohm, 2000; Hoppmann et al., 2013) and cost reductions through economies of scale (Nemet, 2006). In wind power, in contrast, experience generated in government-supported markets was a key driver of product innovation (Andersen, 2004). However, a very large market alone was not sufficient to stimulate innovation in wind turbines, as experience with the early US wind policies suggests (Nemet, 2009). Rather, deployment subsidies in wind power worked best when they were combined with measures to facilitate learning by interacting in the form of knowledge transfer between turbine producers, turbine owners and researchers (Kamp, 2004; Tang and Popp, 2013).

Second, our analysis also provides a starting point to explain the importance of ‘home markets’ for technological innovation which has been observed for some energy technologies but not for others. The technology life-cycle patterns revealed in this study suggest that geographical proximity to users remains important for innovators in complex technologies such as wind power, while it is no longer required in a technology like today’s solar PV. These predictions match very well with the empirical evidence. Two recent, analogous econometric studies analyzed the effect of deployment policies on domestic and foreign innovation in wind power and solar PV. Dechezleprêtre and Glachant (2013) find that domestic wind power deployment policies had an effect on innovation 28 times stronger than foreign ones. In contrast, while there is evidence for such a relationship in the early days of the industry (Hoffmann et al., 2004), Peters et al. (2012) do not find a significant difference between the effects of domestic and foreign deployment policies in solar PV. A similar picture emerges from studies analyzing the effect of deployment policies on the competitive success of domestic firms. On the one hand, comparative studies of wind power in different countries find that domestic deployment policies correlate well with industrial competitiveness.⁴² Lewis and Wiser (2007) conclude from a review of global wind power industry development that domestic deployment policies are “a *pre-requisite* to achieving successful localization” (p. 1855; italics added). On the other hand, recent quantitative studies of the PV industry find that domestic market size is not a good predictor of trade competitiveness (ICTSD, 2010; Algieri et al., 2011). Similarly, recent reports by policy think tanks explicitly compare deployment policy outcomes in the solar PV and wind power industries (Huberty and Zachmann, 2011; Barua et al., 2012). Using trade data, Huberty and Zachmann (2011) find a

⁴² The market leaders of the four largest markets in 2010 – China, the US, India, and Germany – were all domestic companies (BTM, 2011).

correlation between domestic deployment and competitiveness in wind power, but no such relationship in solar PV. They arrive at the conclusion that using domestic demand as an industrial policy “may work for wind turbines, but we find no evidence that it works for solar cells” (p. 1). Similarly, Barua et al. (2012) conclude from a multi-country case study that “domestic deployment is key to building ... domestic industries” in wind power, whereas in PV “a large domestic manufacturing industry and significant domestic deployment do not necessarily go hand-in-hand” (p. 2-3).⁴³ The differing role of geographical proximity is reflected in processes of catching up of emerging economies in the two industries. In wind power, catching up almost always involves significant support for a domestic market, and often required protectionist actions by governments (Lewis, 2007, 2011). The cases of China, Taiwan, and Malaysia, in contrast, which emerged as hubs of PV cell and module production without supporting a significant domestic market, show that countries can reach competitiveness in PV manufacturing without supporting local demand (Liu and Goldstein, 2012; Cao and Groba, 2013).

6.4. Limitations and Further Research

An empirical study as the one presented in this paper has several inherent limitations. Since the validity of the implications formulated above for the design of technology policy hinges on the validity of the applied methodology, three aspects have to be highlighted, which lend themselves as avenues for future research. *First*, using patents as indicators for innovation introduces a bias against process innovations. Since much the relevant information is to be revealed anyway, a product innovation is more likely to be patented than a process innovation, for which inventors may choose other means of appropriability, most notably secrecy. For example, Arundel and Kabla (1998) find that the European machinery firms patented about 52% of product innovations and 16% of process innovations. The fact that we found very few process patents in wind power along the trajectory may be due to a bias against process knowledge in general. This makes careful interpretation of results necessary. However, because this bias should be similar for both technologies, it should not affect the conclusion that there are *significant differences* between the two technologies. Future research could focus on a combination of indicators to assess life-cycle patterns. *Second*, for lack of available citation data, we could not include Chinese patents in our analysis. From a latecomer position China has caught up quickly in clean

⁴³ In 2011, the top five wind markets (according to cumulative installed capacity) were home to 9 of the top 10 turbine suppliers, whereas in PV the top 5 countries were home to only three.

technologies since the early to mid-2000s. Especially in solar PV, Chinese firms have come to dominate the global market. Our patent data shows a surge of Chinese patent filings in both technologies since about 2010. Understanding the Chinese firms' influence on the technological trajectory and the observed life-cycle patterns is highly relevant for the academic literature and the policy community. Once Chinese citation data is systematically available in commercial patent databases, future research should aim to address these questions. *Third*, our broader conclusions need to be validated by characterizing the life-cycles of additional technologies in the energy sector. The fact that the two selected technologies already show significantly different life-cycle patterns suggests that there is much to learn when comparing the more extreme areas of the space mapped in Figure 11. Especially in the lower left and upper right corners of the framework, intuition suggests that empirical analyses could reveal patterns that have so far not been described by the two traditional life-cycle models. Beyond the energy sector, we believe that the methodology and indicators developed in this paper open up promising research opportunities in toward a systematic characterization of life-cycle patterns across a wide range of technologies.

7. Conclusion

Technological change in energy technology can play a major role in mitigating climate change and reducing the environmental footprint of energy production and consumption. To stimulate the necessary innovation, governments will likely spend trillions of USD of public resources on technology policies for clean energy technologies over the coming decades. This paper mapped the patterns of innovation over the technology life-cycle in solar PV and wind power in order to gain insights about how these resources can be spent effectively.

In particular, the paper analyzed which of two common models of innovation over the *technology life-cycle* best describes the pattern of innovation in the two technologies. The results suggest that solar PV technology followed the life-cycle pattern of *mass-produced goods*, a model that typically applies to technologies with relatively simple product architecture and a large-scale production process: early product innovations were followed by a surge of process innovations, especially in solar cell production. Wind power systems, in contrast, more closely resembled the life-cycle of *complex products and systems*, a model that has been developed for technologies with a complex product architecture and low-volume production: the focus of innovative activity shifted over time from the system architecture and core

components to different sub-systems and components of the product, rather than from product to process innovations.

The findings allow to draw conclusions about the patterns of technological learning in energy technologies from the general literature on technology life-cycles, and to make sense of seemingly conflicting evidence about innovation and policy impacts in the two technologies. In solar PV, most innovations after the first large-scale deployment of the technology in the 1980s were focused on the production process, which points toward a predominant role of *learning-by-doing*, *economies of scale in manufacturing* and *innovations in production equipment*. In wind power most innovations introduced novel sub-system and component designs, which points toward the importance of *learning-by-using*, *product up-scaling* and *innovations in operation & maintenance (O&M)*. These differing patterns correspond well with existing studies of technological learning in the two technologies and help putting these studies in comparative context.

Besides the conclusions about the innovation process, the contrasting characterizations of the learning processes in the two technologies have important policy implications, in particular with regard to public policies that subsidize and facilitate large-scale deployment and use of these technologies. The different life-cycle patterns suggest that deployment policies play very different roles in innovation in the two technologies: in a learning process that is centered around the production process, deployment policy support can be crucial to enable learning-by-doing, large-scale production and markets for production equipment; in contrast; in a learning process that is centered around the product design, deployment policy support can be crucial to enable learning-by-using, gradual up-scaling and markets for specialized O&M service providers.

Differing roles of large-scale deployment in the innovation process imply different, technology-specific policy instrument designs. These stand in contrast to the current practice of one-size-fits-all instruments that some governments employ to stimulate energy innovation, e.g., through tax credits or feed-in tariffs for *all* types of renewable electricity, or uniform mandates for *all* kinds of alternative vehicle drive-trains. For *mass-produced goods*, such as solar cells, biofuels, LEDs, batteries or fuel cells, large markets, ideally coordinated internationally, are needed to enable the necessary economies of scale and the learning-by-doing in production – a small market, even if supported over a long time frame, will not overcome the ‘chicken-and-egg’ problem of low production volumes and high production costs. For *complex products and systems*, such as wind turbines, geothermal systems, nuclear power plants, and transport systems, deployment policies have to go beyond simply subsidizing more-

of-the-same in order to fully realize their potential innovation impact. For these technologies, deployment policies should take the form of ‘performance-driven niche markets’, because these policies are most useful if they generate valuable experience from learning-by-using and can enable user-producer interaction, not if they only enable economies of scale and learning-by-doing.

In conclusion, few people would support a 'one-size-fits-all' innovation policy approach for semiconductor, machinery, biotechnology, oil and gas, and chemical industries. The findings of this paper indicate that it may be equally misleading to lump together solar PV systems, wind turbines, biomass gasification, carbon capture and storage, and fuel cells when designing policy instruments to stimulate innovation in clean energy technologies.

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Appendix

Table A1: Main engineering tasks in solar PV product and process development (areas of PV-specific knowledge are shaded in grey)

System element	Product design	Production process
Solar cell	<ul style="list-style-type: none"> Design of cell materials and arrangement Design of electrical contact patterns 	<ul style="list-style-type: none"> Process, equipment and plant design for production of cell materials Process, equipment and plant design for production of solar cell; surface treatment; contact printing Design of optical and electrical testing equipment
Module	<ul style="list-style-type: none"> Design of module circuitry Design of encapsulation materials, back cover and frame 	<ul style="list-style-type: none"> Process, equipment and plant design for cell interconnection, encapsulation, aluminum frame and glass processing Design of optical and electrical testing equipment
Mounting system	<ul style="list-style-type: none"> Design of load carrying structures and control system Transport-, installation-, and O&M-friendly design 	<ul style="list-style-type: none"> Metalworking and assembly Electronics manufacturing and assembly
Grid connection	<ul style="list-style-type: none"> Design and dimensioning of control and power electronics 	<ul style="list-style-type: none"> Electronics manufacturing and assembly

Table A2: Main engineering tasks in product and process development wind power (areas of wind-specific knowledge are shaded in grey)

System element	Product design	Production process
Rotor	<ul style="list-style-type: none"> Development of structural materials and coating Aerodynamic and structural design Choice of rotor control Design and integration of electric motors, gears, hydraulics, control systems and power sources 	<ul style="list-style-type: none"> Processing of composites and core materials Design of specialized molds Design of non-destructive testing equipment and procedures Metalworking, electrical manufacturing and assembly
Power train	<ul style="list-style-type: none"> Design of mechanical drive-train architecture Dimensioning and material selection for hub, bearings, shafts, brakes, gearbox, lubrication, joints and couplings Choice of generator topology Design and dimensioning of generator, power electronics, cooling and control systems 	<ul style="list-style-type: none"> Metalworking and assembly Electrical equipment manufacturing and assembly Electronics manufacturing and assembly
Mounting & encapsulation	<ul style="list-style-type: none"> Design of load transfer, noise insulation and thermal management Aesthetic and aerodynamic design Transport-, installation-, and O&M-friendly design Dimensioning of tower and foundation for static and dynamic load transfer 	<ul style="list-style-type: none"> Composite processing (thermal and chemical process engineering) Metalworking Steel processing Concrete production
Grid connection	<ul style="list-style-type: none"> Design of wind-farm circuitry, voltage transfer, electrical insulation Choice and design of storage technology Design of control strategy and software Design and integration of control system elements 	<ul style="list-style-type: none"> Electrical equipment manufacturing and assembly Electronics manufacturing and assembly

Table A3: Patents along critical path of solar PV citation network 1963-2009

Priority patent	Application	Focus of invention	Focus of invention	Assignee	Assignee type
US 3,978,333	15-Apr-74	Cell concept (polycrystalline silicon)	Cell (product)	E. Crisman	Individual
US 4,064,521	28-Jul-75	Cell concept (amorphous silicon)	Cell (product)	RCA	Cell manufacturer
US 4,126,150	28-Mar-77	Non-reflecting surface layers for solar cell	Cell (product)	RCA	Cell manufacturer
US 4,162,505	24-Apr-78	Cell concept (amorphous silicon)	Cell (product)	RCA	Cell manufacturer
US 4,272,641	19-Apr-79	Cell concept (tandem junction amorphous silicon)	Cell (product)	RCA	Cell manufacturer
US 4,419,530	11-Feb-82	Procedure to connect cells in module	Module (process)	Energy Conversion Devices Inc.	Cell manufacturer
US 4,443,652	9-Nov-82	Cell interconnection in module	Module (product)	Energy Conversion Devices Inc.	Cell manufacturer
US 4,514,583	7-Nov-83	Substrate sheet for thin-film module	Cell (product)	Energy Conversion Devices Inc.	Cell manufacturer
US 4,677,250	30-Oct-85	Substrate sheet for thin-film module	Cell (product)	Astrosystems Inc.	Cell manufacturer
US 5,087,296	26-Jan-87	Production process for polycrystalline thin-film cell	Cell (process)	Canon	Cell manufacturer
US 5,130,103	24-Aug-87	Production process for crystalline thin-film cell	Cell (process)	Canon	Cell manufacturer
US 5,094,697	16-Jun-89	Production process for crystalline thin-film cell	Cell (process)	Canon	Cell manufacturer
US 5,403,771	26-Dec-90	Production process for polycrystalline thin-film cell	Cell (process)	Canon	Cell manufacturer
US 5,856,229	10-Mar-94	Production process for crystalline thin-film cell	Cell (process)	Canon	Cell manufacturer
US 5,854,123	10-Mar-94	Production process for silicon-on-insulator cell	Cell (process)	Canon	Cell manufacturer
US 6,326,280	2-Feb-95	Production process for crystalline thin-film cell	Cell (process)	Sony	Cell manufacturer
US 6,294,478	28-Feb-96	Production process for silicon-on-insulator cell	Cell (process)	Canon	Cell manufacturer
US 6,054,363	15-Nov-96	Production process for silicon-on-insulator cell	Cell (process)	Canon	Cell manufacturer
US 6,221,738	26-Mar-97	Production process for silicon-on-insulator cell	Cell (process)	Canon	Cell manufacturer
US 6,582,999	12-May-97	Production process for silicon-on-insulator cell	Cell (process)	Silicon Genesis Corp.	Production equipment provider
US 6,613,678	15-May-98	Production process for silicon-on-insulator cell	Cell (process)	Canon	Cell manufacturer
US 6,664,169	8-Jun-99	Production process for microcrystalline cell	Cell (process)	Canon	Cell manufacturer
US	16-Aug-00	Production process for silicon-germanium-	Cell (process)	Massachusetts Institute of	Public sector

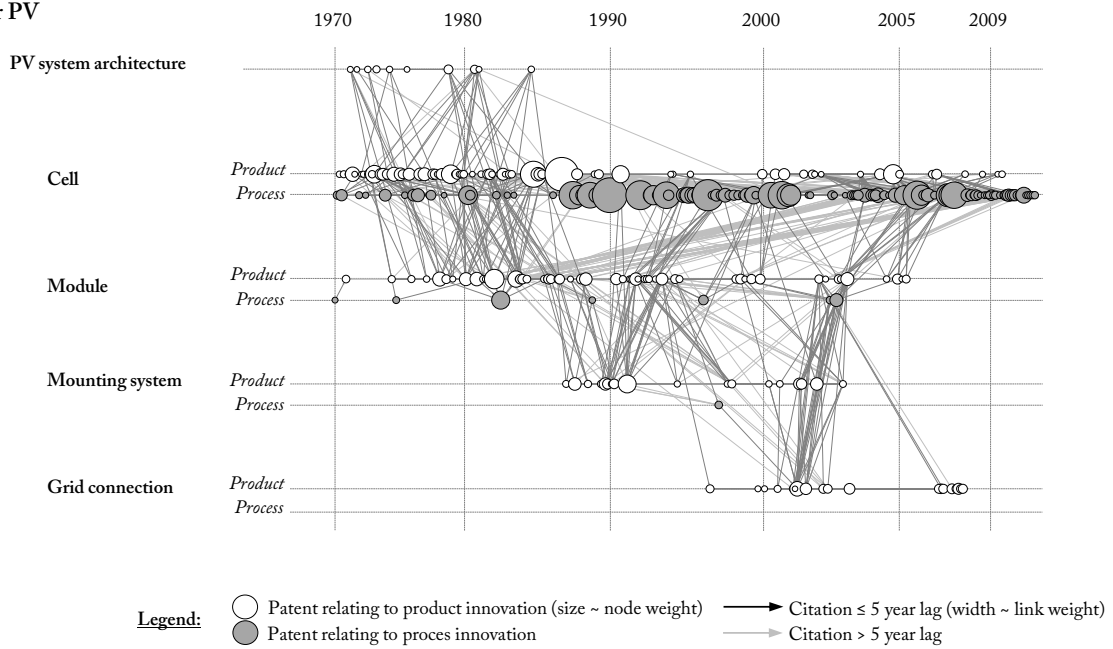
6,573,126		on-insulator based cell		Technology	
US 6,794,276	27-Nov-00	Production process for a substrate for thin-film solar cell	Cell (process)	Soitec Technologies	Cell manufacturer
US 7,019,339	17-Apr-01	Production process for germanium heterostructure cell	Cell (process)	California Institute of Technology	Public sector
US 7,341,927	17-Apr-01	Production process for silicon heterostructure cell	Cell (process)	California Institute of Technology	Public sector
US 7,846,759	21-Oct-04	Multi-junction cell concept	Cell (product)	Aonex Technologies	Materials supplier
US 7,911,016	27-Jul-05	Production process for thin-film cell	Cell (process)	Silicon Genesis Corp.	Production equipment provider
US 7,759,220	5-Apr-06	Production process for thin-film cell	Cell (process)	Silicon Genesis Corp.	Production equipment provider
US 7,655,542	23-Jun-06	Production process for microcrystalline silicon cell	Cell (process)	Applied Materials	Production equipment provider
US 8,203,071	18-Jan-07	Production process for thin-film multi-junction cell	Cell (process)	Applied Materials	Production equipment provider
US 7,875,486	10-Jul-07	Production process for thin-film cell	Cell (process)	Applied Materials	Production equipment provider
US 7,908,743	31-Aug-07	Method of forming contacts on thin-film cell	Cell (process)	Applied Materials	Production equipment provider
US 8,062,922	5-Mar-08	Production process for thin-film cell	Cell (process)	Global Solar Energy	Cell manufacturer
US 8,318,530	24-Jul-09	Production process for thin-film cell	Cell (process)	Solopower	Cell manufacturer

Table A4: Patents along critical path of wind-patent citation network 1963-2009

Priority patent	Application	Focus of invention	Focus of invention	Assignee	Assignee type
SE 005,407	12-May-75	Blade with integrated over-speeding control mechanism	Rotor (product)	Svenning Konsult AB	Engineering consultancy
DE 2,655,026	4-Dec-76	Rotor-hub arrangement with teetering hub and two blades	Rotor (product)	U. Huetter (Indiv.)	Individual
US 4,297,076	8-Jun-78	Control system for two-bladed rotor with adjustable tips	Rotor (product)	MAN	Turbine manufacturer
US 4,274,807	31-Jul-78	Three-bladed turbine with hydraulic pitch mechanism	Rotor (product)	C E Kenney (Indiv.)	Individual
US 4,366,387	10-May-79	Two-bladed downwind turbine with teetering hub and aerodynamic pitch mechanism	Rotor (product)	Carter Wind Power	Turbine manufacturer
US 4,435,646	24-Feb-82	Rotor with teetered hub and mechanical pitch control system	Rotor (product)	North Wind Power	Turbine manufacturer
US 4,565,929	29-Sep-83	Two-blade turbine with novel drag brake and control system	Rotor (product)	Boeing	Turbine manufacturer
US 4,703,189	18-Nov-85	Torque control system for variable-speed power train	Power train (product)	United Technologies	Turbine manufacturer
US 4,700,081	28-Apr-86	Operation strategy for variable-speed power train	Power train (product)	United Technologies	Turbine manufacturer
US 5,083,039	1-Feb-91	Variable-speed power train architecture and power control	Power train (product)	US WindPower	Turbine manufacturer
US 5,155,375	19-Sep-91	Speed control system for variable-speed power train	Power train (product)	US WindPower	Turbine manufacturer
US 5,652,485	6-Feb-95	Power train control for variable wind conditions	Power train (product)	U.S. EPA	Public sector
US 6,137,187	8-Aug-97	Variable-speed power train architecture and power control	Power train (product)	Zond Energy Systems	Turbine manufacturer
US 6,566,764	23-May-00	Variable-speed power train adapted to smoothen power output	Power train (product)	Vestas Wind Systems	Turbine manufacturer
US 6,670,721	10-Jul-01	Inverter control system for grid-friendly power output	Grid connection (product)	ABB	Generator supplier
DE 1,048,225	28-Sep-01	Collective control method for turbines in a wind farm	Grid connection (product)	Enercon	Turbine manufacturer
US 7,190,085	8-Apr-03	Variable-speed power train architecture	Power train (product)	Alstom	Generator supplier
US 7,042,110	7-May-03	Variable-speed power train architecture	Power train (product)	Clipper Windpower	Turbine manufacturer
US 7,205,676	8-Jan-04	Generator control optimizing response to grid failure	Grid connection (product)	Hitachi	Turbine manufacturer
JP 055,515	27-Feb-04	System to control nacelle vibrations	Mounting & encapsulation (product)	Mitsubishi HeavyInd.	Turbine manufacturer
US	30-Sep-04	System to control turbine vibrations	Mounting &	General Electric	Turbine

7,309,930			encapsulation (product)		manufacturer
US 7,342,323	30-Sep-05	Power train control routine based on upstream wind measurements	Power train (product)	General Electric	Turbine manufacturer
US 7,400,055	1-Feb-06	Control routine to suppress tower vibrations	Mounting & encapsulation (product)	Fuji Heavy Industries	Turbine manufacturer
US 7,851,934	14-Sep-06	Control routine to respond to grid faults	Grid connection (product)	Vestas	Turbine manufacturer
US 7,911,072	14-Sep-06	Control routine to respond to grid faults	Grid connection (product)	Vestas	Turbine manufacturer
US 7,714,458	22-Feb-08	Control routine to respond to grid-side load shedding	Grid connection (product)	Nordex	Turbine manufacturer
US 7,949,434	16-Jun-08	Control system for wind farm with redundant control unit	Grid connection (product)	Nordex	Turbine manufacturer

a) Solar PV



b) Wind power

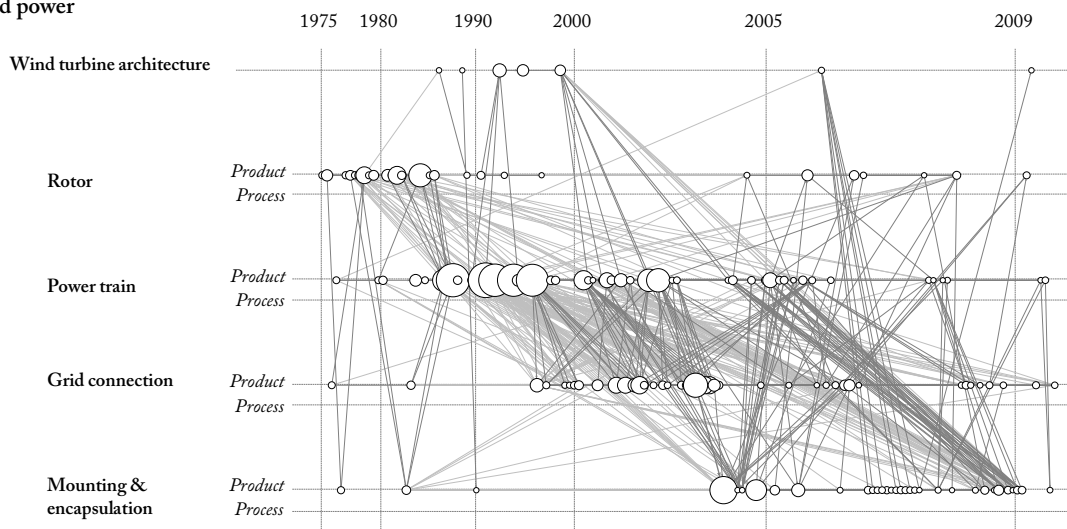


Figure A 1: Patents in 80%-weight network (full networks D in Table 4) ordered by time of patent filing and their focus in the technological system; linkages indicate citations.

The Effect of Local and Global Learning on the Cost of Renewable Energy in Developing Countries[♦]

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Abstract

High upfront costs are a critical barrier for investments in clean infrastructure technologies in developing countries. This paper uses a case study of Thailand's electricity sector to create realistic estimates for the relative contributions of local and global technological learning to reducing this cost in the future and discusses implications of such learnings for international climate policy. For six renewable electricity technologies, we derive estimates for the share of locally and globally sourced goods and services, and analyze the effects of local and global learning during the implementation of Thailand's renewable energy targets for 2021. Our results suggest that, in aggregate, the largest potential for cost reduction lies in local learning. This finding lends quantitative support to the argument that the conditions enabling local learning, such as a skilled workforce, a stable regulatory framework, and the establishment of sustainable business models, have a more significant impact on cost of renewable energy in developing countries than global technology learning curves. The recent shift of international support under the United Nations Framework Convention on Climate Change towards country-specific technology support is therefore promising. However, our results also show that the relative importance of local and global learning differs significantly between technologies, and is determined by technology and country characteristics. This suggests that international support need to consider both the global perspective and local context and framework conditions in order to reap the full benefits of technological learning across the wide range of clean technologies.

Keywords: Climate policy, Technology transfer, Technological capabilities, Technological learning, Thailand, Renewable energy

Highlights:

- Development of a techno-economic model of Thailand's Alternative Energy Development Plan 2012-2021.
- Analysis of the impacts of local and global learning effects on mitigation cost.
- Demonstration that the importance of global and local learning varies between clean technologies.
- Finding that local learning is significant for wind, PV, biogas and micro hydro, whereas global learning is important for PV and solar thermal.
- Discussion of the future role of the international support for clean technologies.

1. Introduction

The global climate policy regime needs to significantly accelerate the diffusion of clean technologies to avoid dangerous impacts from climate change (UNFCCC, 2012). In addition to actions taken by the developed world, developing countries are expected to assume greater responsibility by implementing domestic policies that contribute to both domestic economic development and climate change mitigation (Kanie et al., 2010). Indeed many developing countries are already implementing domestic climate legislation, despite the gridlock in international negotiations (Nachmany et al., 2014; REN21, 2013; Townshend et al., 2013). However, high upfront costs remain a critical barrier for large-scale investments in clean technologies, especially in developing countries (IPCC, 2012; Schmidt, 2014). How to accelerate the development and transfer of clean technologies is, therefore, emerging as a central issue in the international climate policy negotiations (Ockwell and Mallett, 2012; Pueyo et al., 2012).

Experience in the industrialized world has shown that cost reductions and performance improvements of new technologies are often closely linked to policies aimed at increased production and deployment (Jänicke, 2012), driven by mechanisms collectively referred to as *technological learning* (Junginger et al., 2010). If successful, the increasing number of mitigation actions taken now by developing countries holds the promise to stimulate innovations and future cost reductions there as well. But technological learning encapsulates a diverse array of purposeful processes that some countries, sectors and organizations manage better than others (Bell and Figueiredo, 2012; van Hoof, 2014). Besides creating financial incentives for investment, one of the key challenges for international climate policy is therefore to actively promote technological capabilities in developing countries and to enable countries to reap the full learning benefits from mitigation investments they make and attract (Benioff et al., 2010; Bhasin, 2013; de Coninck et al., 2008; Ockwell and Mallett, 2012).

Technological learning in developing countries, especially outside the largest emerging economies, follows distinct dynamics (Pueyo et al., 2011). The industries producing clean technologies are increasingly globalized (Gallagher, 2014; Lewis, 2012; Nahm and Steinfeld, 2014). Therefore, in a typical investment project, local firms in developing countries provide only part of the products and services. Learning in this share of the industry value chain is local in nature and driven by local market developments and policies – we will refer to it as *local technological learning* (Morrison et al., 2008; Mytelka, 2000). However, because a substantial share of components is typically sourced from abroad, the economics of local investments are also impacted by technological learning processes in other

countries. For example, technological progress by Chinese solar cell producers improves the economics of solar investments around the world. This form of learning is driven more by global markets than by policies in individual countries (Peters et al., 2012). Future investment conditions for clean technologies in developing countries thus depend on a combination of global and local learning processes, which, in turn, depend on domestic and international regulatory, institutional and industrial contexts. Better understanding of the relative importance of the two can improve both domestic and international policy decisions.

Using a quantitative case study, this paper estimates the effect of local and global technological learning on the cost reductions of renewable electricity generation in Thailand. We employ a techno-economic model of the country's electricity sector to project the cost of implementing the country's renewable energy targets for 2021 (Kamolpanus, 2013). We derive estimates for the share of locally and globally sourced goods and services for six renewable electricity technologies and analyze, in different scenarios, the impact of local and global learning effects on the investment cost. Based on the results, we explore implications for the design of international low carbon technology support mechanisms.

The paper makes three main contributions. First, our case study informs the academic debate as well as international negotiations on the post-Kyoto climate policy regime of the United Nations Framework Convention on Climate Change (UNFCCC). In its support for technology development and transfer, the international climate policy regime has recently shifted its attention toward national policies and local technological learning. The analysis presented in this paper enhances the understanding of the merits of this shift, and informs the design and functional specification of the new international technology support mechanisms. Our quantitative approach and the focus on mitigation cost complements existing conceptual and qualitative work on the topic (Benioff et al., 2010; Bhasin, 2013; de Coninck et al., 2008; Ockwell and Mallett, 2012). Furthermore, it contributes to the growing body of literature on the economics of clean energy technology investments in developing countries (e.g., IRENA, 2012a; Schmidt et al., 2012). Finally, our paper is among the first to investigate the impact of local and global learning separately for a specific developing country case.

The next section will introduce the key theoretical constructs used in the analysis (Section 2). Section 3 introduces the case, before section 4 presents the model, the data sources, and the methodology. The results of the case study are presented in Section 5, and their policy implications discussed in Section 6.

2. Local and Global Technological Learning

2.1. Technological Learning in Developing Countries

Technological learning is understood here broadly as the accumulation of technological knowledge and experience, often also referred to as *technological capabilities*, in individuals and organizations (Bell and Figueiredo, 2012). Research on innovation processes has shown that the technological capabilities held by firms comprises not only information codified in capital goods or documents (patents, manuals, etc.), but also includes the tacit knowledge embodied in individual skills and firm routines (Dosi, 1988; Senker, 1995). These elements of knowledge are costly to transfer and therefore highly organization-specific (von Hippel, 1994). This means that removing trade barriers and providing developing countries with intellectual property rights (IPR) and resources for technology imports is not sufficient to enable countries to catch up to the technological frontier (Bell and Pavitt, 1996; Ockwell et al., 2010). Rather, catching up requires building local technological capabilities through the cumulative, costly and time-consuming process of technological learning (Bell, 2010).

Technological capabilities and learning are increasingly being recognized as significant drivers of low carbon development (Byrne et al., 2011; Lema and Lema, 2013; Phillips et al., 2013). The international climate negotiations, too, are taking notice (Ockwell and Mallett, 2012). Improved technological capabilities hold the promise of removing barriers to the diffusion of clean technologies, thereby facilitating further emission reductions in the future (Sandén and Azar, 2005). Besides its effect on mitigation cost, the local build-up of technological capabilities is crucial for local industrial capacity, poverty reduction and economic growth. For many developing countries, investing in climate change mitigation is, for now, only desirable if the government can create opportunities for the local private sector to participate in the value chain of mitigation investments. However, in order to participate in the development and manufacturing of clean technologies, local firms in developing countries need to create the capacity to continuously absorb, adapt and improve new technologies (Bell and Pavitt, 1996).

Climate models increasingly incorporate learning as an endogenous process driven by mitigation investments (Kahouli-Brahmi, 2008; van der Zwaan et al., 2002), but technological learning is not an automatic by-product of investments (Bell and Figueiredo, 2012). Rather, in the analysis of the development of mitigation policies and estimation of future mitigation cost, it is better understood as an *opportunity* that can be only adequately seized when both governments and firms create the

necessary conditions. Organizations need to pursue conscious efforts to create the ability, in the form of a skilled workforce and organizational processes, to *absorb* the new knowledge and experience that they generate (Cohen and Levinthal, 1989). Furthermore, organizations innovate and learn through their interaction with users, suppliers, competitors, universities or regulators in *systems of innovation* (Fagerberg et al., 2007; Lundvall et al., 2009). The existence of formal and informal networks, as well as public funding for science and technology, are therefore critical drivers of technological learning. And, last but not least, learned capabilities degenerate rapidly if organizations have a rapid workforce turnover, face an instable regulatory framework, or pursue unsustainable business models.

2.2. Local and Global Learning Effects in Value Chains

Most clean technologies are technological systems consisting of hundreds, or even thousands, of materials, components, and intermediate goods. Furthermore, mitigation investments involve numerous legal, financial, and regulatory services. The collective of technology suppliers and service providers that deliver the materials, components, products and services to deploy technologies we call the technologies' *industry value chain*.

Modern industry value chains are disintegrated and geographically distributed production and service networks. As markets for clean technologies have grown, their supplying industries have also globalized in recent years (e.g., Gallagher, 2014; Lewis, 2012; Nahm and Steinfeld, 2014). Globally traded components and products are often those that can be transported at relatively low cost and have standardized interfaces. (On the extreme end of this spectrum are commodities.) Globally traded services often require highly specialized technological expertise that only very few firms possess. In the wind turbine industry, for example, gearboxes, hubs, generators and bearings are components for which the know-how necessary for design and manufacturing is concentrated in only a few key firms globally. Further, the consulting services needed to make a complex product bankable, or a difficult geography accessible, are often provided by experienced, globally operating firms.

For technological learning in globally traded goods and services, global market conditions matter more than *where* their products are finally deployed. If uncertainty about the product's performance is very large, as in the case of carbon capture and storage technology, any demonstration will add to the global knowledge pool (de Coninck et al., 2009). In the case of smaller components, materials, or intermediate goods, producers seldom even interact with end-users, if they know them at all. In the case of services, the global applicability of their experience is the key reason why globally operating producers are selected in the first place. The accumulation of capabilities in firms and industries is

therefore more dependent on global, aggregate market trends than on country-specific context factors. We define learning in these goods and services as *global technological learning*, because, in a simplified learning model or experience curve, it would best be predicted by the size of the *global* market.

But value chains are not entirely globalized. To stimulate local private sector participation, many climate-related laws in developing countries contain some form of provision to create a certain level of domestic content. This gives local firms economic advantages over global suppliers. But even without legislative requirements, often local firms provide many steps. This may include large and heavy components that are costly to transport, or factors which are cheaper to make at home; but it is important to note that the drivers underlying these patterns are not affected only by input or transportation cost. The drivers for localization may include the expertise required to deal with idiosyncratic geography, context-specific or fast-changing regulations, or local infrastructure and climate conditions. In a wind power project, for example, towers, blades, and foundations are typically sourced from suppliers not far from the project site, and domestic firms often provide project development, installation, operation, and maintenance services. In developing countries, it is reasonable to assume that local firms are mostly active in their home markets. We will therefore assume that their learning is predominantly local, and refer to technological learning in this part of the value chain as *local technological learning*.

The geographical dispersion of value chains leads to cost and cost trends that differ significantly between components (e.g., Lindman and Söderholm, 2011). Cost trends and learning curves are global whenever global markets exist, while for the locally sourced components trends differ substantially between regions (e.g., Seel et al., 2014). For the latter, local economic, political, and regulatory conditions determine whether or not investments lead to the accumulation of technological capabilities, which in turn are essential to reduce local investment cost. To stimulate progress in this part of the value chain, domestic and international policymakers should focus on strengthening the domestic innovation system. For the global part of the value chain, however – which also affects domestic investment economics – national innovation systems are not very important. Here, policymakers need to work toward international knowledge sharing and standardization activities to strengthen the sectoral innovation system in order to advance low-carbon technologies (de Coninck et al., 2009). They should also strive for the global markets to remain open and try to minimize protectionism to reap the benefits of global technological learning (Lewis, 2014).

3. The Case of Thailand's Electricity Sector

3.1. Case Selection

This paper presents a quantitative case study of Thailand's Alternative Energy Development Plan (DEDE, 2012) for the electricity sector in order to explore the relative importance of local and global learning in developing countries' mitigation efforts. We chose a case study of the electricity sector because it lies at the heart of the climate change challenge as the single largest source of CO₂ emissions among the primary sectors of the world economy (Bazilian et al., 2008). Indeed, the majority of national mitigation policies in developing countries target energy production and consumption in the industrial, energy supply, buildings, and transport sectors (van Tilburg et al., 2013). At the same time, the diversity of technologies in the electricity sector and their globally operating technology providers allows us to model both local and global learning processes.

We chose Thailand as case study for three reasons. First, the country has clear, broad and ambitious targets for renewable energy diffusion which allow us to study the impact of different learning conditions on the cost of an existing policy. Second, the country's government publishes detailed data on energy production and consumption that allow us to model the electricity sector on a single-plant level. Third, the country faces economic and political challenges that make the framework conditions for its energy policy decisions representative of a large number of other middle-income countries. A country of 66.9 million with a GDP per capita at USD 5,210, Thailand has managed to provide its population with almost universal access to electricity (The World Bank, 2014). Like many other middle-income countries, it now faces the challenge of rapidly growing energy consumption, accompanied by growing carbon emissions, import dependency, national security concerns and local resistance to fossil and nuclear power plants. How to assist emerging economies in managing these challenges while simultaneously reducing carbon emissions will be one of the most important questions for international climate policy in the coming decades.

3.2. Trends and Challenges

Primary energy consumption in Thailand has almost tripled from 1990 to 2011, making it the second-largest energy consumer in the Association of Southeast Asian Nations (ASEAN), while subsequently its greenhouse gas (GHG) emissions grew by 177.5% (see Figure 1). The power sector is the largest carbon source, with a share in national emissions that grew from 33% in 1990 to 42% in 2011. By

2035, energy consumption and GHG emissions are expected to roughly double yet again (IEA, 2013a).

Thailand is already a net importer of oil, gas and coal, and is projected to become the most energy import-dependent country among the ASEAN by 2035, with imports estimated to increase to about 90% of consumed oil and gas (IEA, 2013a). Nakawiro et al (2008) estimate that gas and coal import costs will grow from 0.92% of the country’s GDP in 2011 to 2.19-2.69% in 2025, depending on the development of fuel prices in the region. The main domestic sources are not without challenges, too, in light of strong local opposition to nuclear power and new coal plants (Greacen and Bijoor, 2007; Pongsoi and Wongwises, 2013).⁴⁴

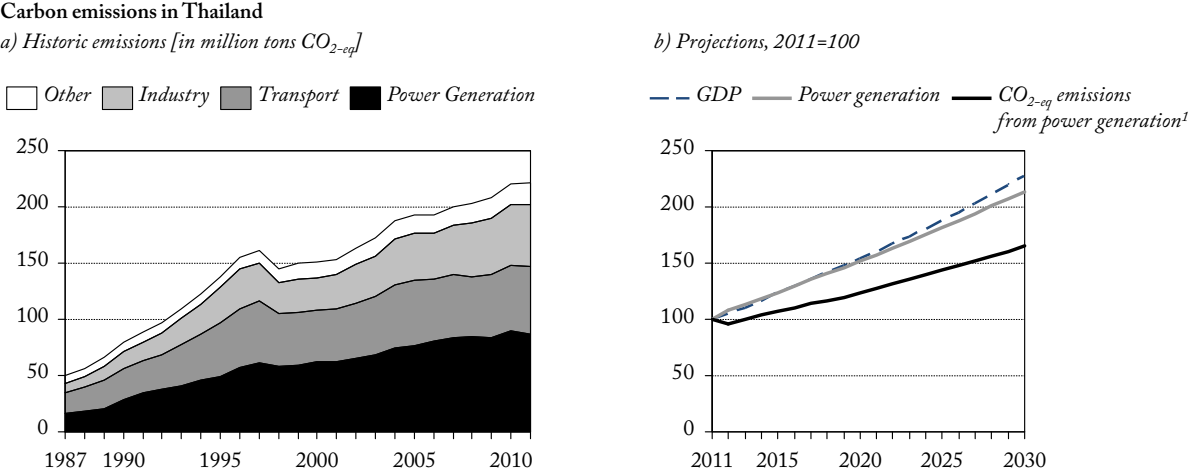


Figure 1: Thailand’s carbon emissions by sector (a) and future projections for emissions from the country’s power sector (b). ¹CO₂ emissions from power sector do not contain imports. Data from EPPO (2013, 2012a).

As of 2011, the electricity sector is dominated by natural gas (67%), with lignite and hard coal providing together about 20% as well (Figure 2). Besides large hydropower (5%), renewable energy constitutes only a very small part of the electricity mix, mostly in the form of biomass (1.4%) (EPPO, 2012b). The remaining demand is covered by direct electricity imports (6.6%). Electricity generation reached 162 TWh in 2011 and is projected to increase by more than 4% annually (EPPO, 2012b, 2012c). Besides domestic capacity investments, the government plans to meet demand by increasing the share of direct electricity imports from neighboring Malaysia and Laos to 13% in 2030 (Figure 2).

⁴⁴ The first nuclear plant was originally scheduled to come online in 2020, but was postponed to 2026 after the nuclear incidence in Fukushima, Japan, in 2011.

Planned fuel mix of the electricity sector in Thailand 1987-2030

Electricity production by source, TWh

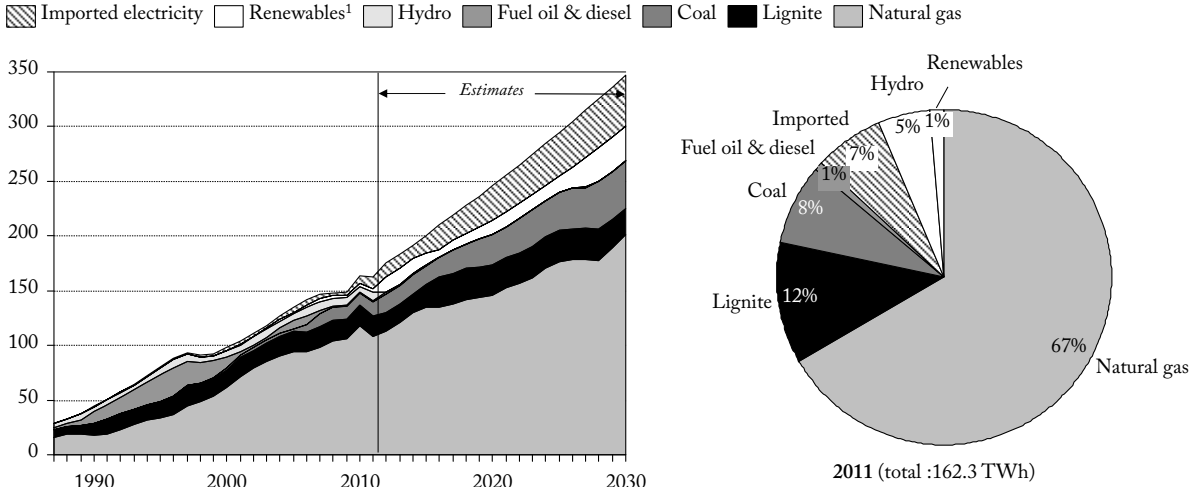


Figure 2: Development of the fuel mix in Thailand’s power sector from 1987 to 2030. ¹The renewables wedge contains hydropower after 2011; the share of renewables after 2012 reflects relatively conservative projections of the Power Development Plan. Data from EPPO (2013, 2012a).

3.3. Targets and Support for Renewable Energy

In recent years, electricity sector planning initiatives have begun to consider renewable energy as a potential remedy for some of the problems the country faces. Thailand has no official renewable energy law at this point but several comprehensive long-term energy plans (Tongsopit and Greacen, 2013). The two most important are the Power Development Plan by the Energy Policy and Planning Office (EPPO, 2012c) and the Alternative Energy Development Plan (AEDP) by the Department of Alternative Energy Development and Efficiency (DEDE, 2012; Kamolpanus, 2013), both under the Ministry of Energy. The AEDP, updated in 2013, is aiming to increase the renewable energy in the power sector to 14 GW by 2021, or 24% of the total capacity (compare with Figure 2). As shown in Figure 3, the largest part of this capacity is projected to come from biomass (4.8 GW), followed by biogas (3.6 GW), solar power (3 GW), wind power (1.8 GW) and micro hydro (324 MW).⁴⁵ The largest relative increase is targeted for biogas (17-fold) and wind energy (15-fold). It is notable that large hydro is not part of the AEDP. For simplification, we therefore use the term ‘renewable electricity’ in this paper to refer to non-large-hydro renewable electricity technologies.

⁴⁵ The targets include another 400 MW of municipal waste incineration plants.

Targets for renewable energy development in Thailand in 2012-2021

Electric power generation capacity by source, MW

■ Status end of 2012 ■ Targets for 2021

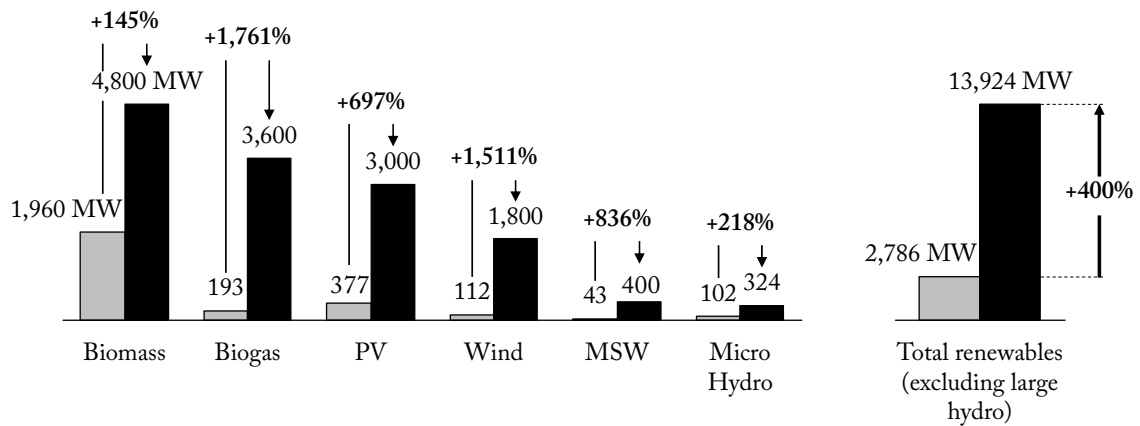


Figure 3: Targets for renewable electricity under Thailand's Alternative Energy Development Plan (DEDE, 2012). Data for 2012 are from DEDE (2013); updated targets for 2021 from Kamolpanus (2013).

In addition to public research, tax incentives, venture capital and investment grants, the primary government policy to induce renewable energy investments is currently a feed-in tariff premium scheme, referred to as 'FIT adder' (DEDE, 2012; Tongsovit and Greacen, 2013). The FIT adder program provides a purchase guarantee under which fixed premiums, which differ by technology, capacity and project location, are paid on top of a base tariff that is determined by the utility's avoided cost. Originally implemented in 2007, the official objectives of the FIT adder policy included enhanced levels of renewable energy generation; private sector involvement; economic growth and rural development; diversification of the fuel mix; local pollution reduction and utilizing agricultural wastes; as well as local equipment manufacturing and thus reduced international equipment imports (Tongsovit and Greacen, 2013). In 2010, Thailand's government announced plans to transform the FIT adder into a fixed FIT, but has done it so far only for rooftop solar PV (Kamolpanus, 2013). There is no local content requirement in Thailand's renewable electricity support policies, but import duties create incentives to source locally (Beerepoot et al., 2013).⁴⁶

⁴⁶ These import duties were not considered in our analysis.

3.4. Local and Global Learning in Renewable Energy in Thailand

As developed in Section 2, modern clean technology value chains feature significant local and global value creation. To illustrate how the local and global aspects of the value chain play out in Thailand, the value chain of a typical project in the electricity sector in Thailand is shown in Figure 4. Displayed is a value chain of a solar PV project, including the primary value chain, from material and component suppliers, up to the grid operator, and secondary activities such as universities, consultancies or legal services. For one specific project, a 9.5 MW solar PV project in Mae Chan in Chiang Rai province developed in 2013, we identified the most likely countries of origin for each value chain step. In the depicted case the project operator, the grid operator, the construction company, one of the two project developers, (probably) legal and financial services, and the regulator are local, while no core hardware components were manufactured in Thailand. The modules are manufactured by a Norwegian company in Singapore, while the inverters are made by a Swiss-Swedish company, most likely in Estonia. The leading production equipment suppliers, material suppliers and research institutes are located in Europe, the United States and Australia, thus it is almost certain that all these countries/continents are also represented in the value chain. The economics of the final project are determined by progress by all these actors in a concurrence of local and global learning effects, which calls for policy support that strengthens learning conditions locally and globally to facilitate overall technological progress.

Local and global value chain for a solar PV power project in Thailand
Origin of actors in value chain of Sonnedix's 9.5 MW project in Mae Chan, Chiang Rai

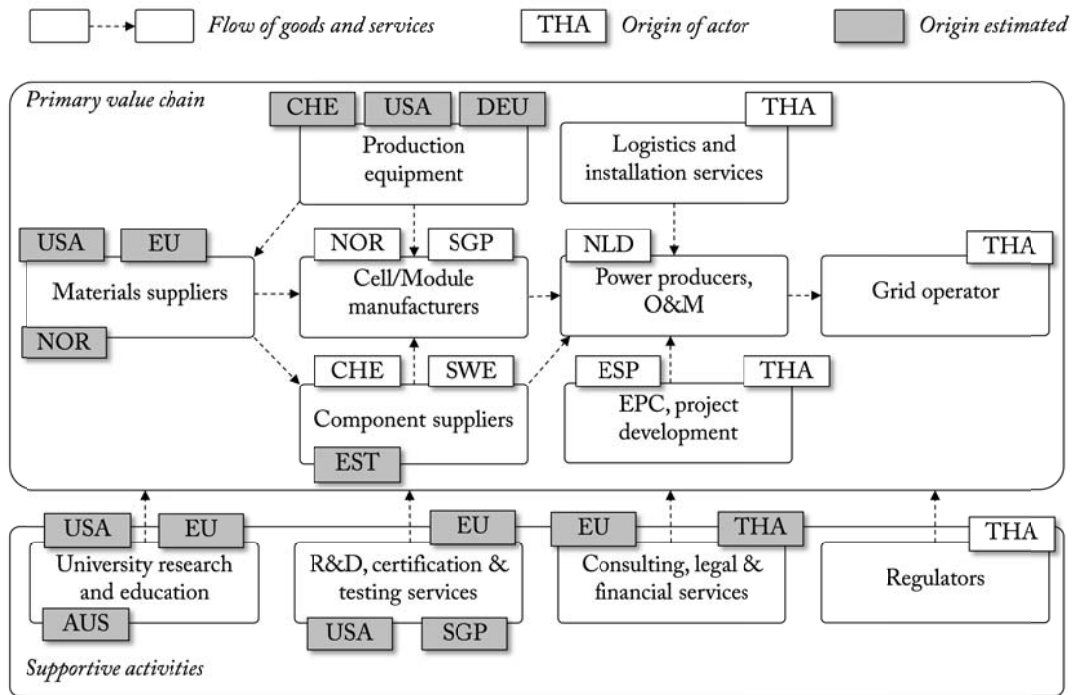


Figure 4: Value chain for an exemplary solar PV project in Thailand. Country codes as defined by UN Statistics Division; EU stands for European Union. Companies were identified from news sources.

4. Materials and Methods

4.1. General Model Framework

We developed a model of Thailand's electricity sector and used different scenarios to estimate the effects of technological learning on the cost of achieving the Alternative Energy Development Plan (AEDP) targets. We chose a bottom-up, techno-economic model (Berglund and Söderholm, 2006) because it allows us to study the effects of cost dynamics on the technology-level on the aggregate cost of renewable energy policies (Kahouli-Brahmi, 2008). To model the effects of learning on the cost of technologies, we chose the learning curve approach because it enables us to treat local and global effects separately (Hayward and Graham, 2013). We focused on six renewable energy technologies under the AEDP: biomass, biogas, micro hydro, on-shore wind, solar PV, and concentrating solar power (CSP).

Model structure

Key relationships between input and output variables (function of technology i , year t)

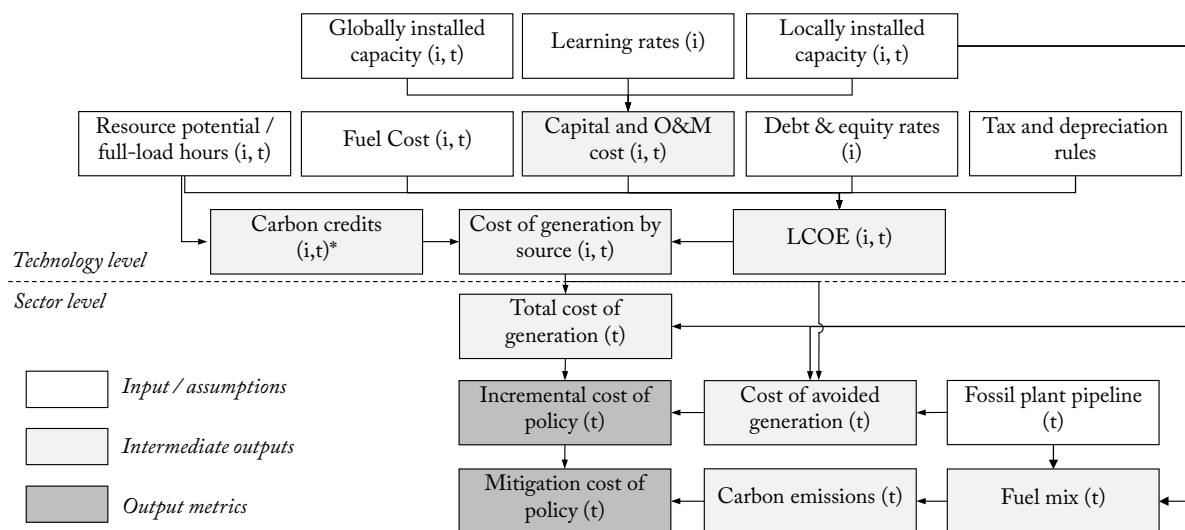


Figure 5: Relationships between key input and output metrics in the techno-economic model; the upper half of the graphic shows variables calculated on the technology-level; the lower half shows variables calculated for the entire electricity sector/policy.

The overall structure of the model with its key variables and relationships is depicted in Figure 5. Calculating the cost of renewable electricity is a well-established process in renewable energy policy analysis (Burtraw et al., 2012). The cost of the avoided electricity, however, even though at least equally important, is often neglected (Schmidt et al., 2012). To obtain the cost of avoided electricity and the avoided greenhouse gas emissions, we compared different scenarios for diffusion of renewable energy with a hypothetical scenario without any renewables diffusion. Based on this comparison, the model provides two main outcome metrics, shown in dark grey in Figure 5, to assess the policy support needed to achieve Thailand’s renewable electricity targets: the *incremental policy cost* and the *mitigation cost*, both stated as net present value.⁴⁷ The former is a proxy for marginal social cost (Palmer and Burtraw, 2005), while the latter allows comparisons between different mitigation measures and carbon prices.

How the scenarios deviate from the non-renewables scenario is calculated on the sectoral level. The incremental costs represent the difference between the total cost of renewable electricity and the total

⁴⁷ The incremental costs and the mitigation costs are discounted to the year 2012 with the yield of 40-year Thai government bonds, which reflects the refinancing cost of the Thai government over the period of the assumed feed-in Tariff payments.

cost of avoided electricity (Schmidt et al., 2012). The mitigation costs are calculated based on the total carbon emission reductions from the AEDP and the incremental cost:

$$\begin{aligned}
 & (i) \text{ Incremental policy cost} \\
 & \quad = \text{Cost of renewable electricity} \\
 & \quad \quad - \text{Cost of avoided electricity [in USD or } \frac{\text{USD}}{\text{MWh}} \text{]} \\
 & (ii) \text{ Mitigation cost} = \frac{\text{Incremental cost}}{\text{Avoided greenhouse gas emissions}} \left[\frac{\text{USD}}{\text{tCO}_2} \right]
 \end{aligned}$$

For each of the renewable and fossil technologies in the sector we calculated the cost of electricity generation for each year of the considered period. The cost of renewable electricity and the cost of avoided electricity were then aggregated from the technology-level calculations. The cost of renewable electricity was aggregated over the renewable technologies under the AEDP in 2013-2021 (details in Section 4.2). The cost of avoided electricity was aggregated over the 9 main fossil technologies from 2013, when the electricity is displaced, to 2040, when the last renewable plant goes offline. How we calculated the avoided cost and avoided emissions is explained in detail in Appendix A.

4.2. Cost of Renewable Electricity Generation

4.2.1. Generated Electricity

The electricity generated by each source of renewable electricity is a function of the diffusion path and the plant utilization. Since the AEDP does not contain interim targets, we modeled the diffusion of the six considered technologies as a linear increase in installed capacity. The split between PV and CSP in the (undifferentiated) total solar target is assumed as a relation of 9 (PV) to 1 (CSP). All renewable electricity is assumed to be fed into the grid (no curtailment), so the plant utilization is a mere function of the resource potential. In the case of micro hydro, biogas and biomass, for which significant domestic experience exists, we took the capacity values from domestic academic sources (Delivand et al., 2011; Pattanapongchai and Limmeechokchai, 2011a; Promjiraprawat and Limmeechokchai, 2012). For wind, solar PV and CSP we estimated the capacity factors based on resource information from the IRENA global atlas (3Tier layer; IRENA, 2014).

4.2.2. Cost per Unit of Generated Electricity

To model the cost of electricity, we assumed that the government supports each technology with an inflation-adjusted, fixed feed-in tariff (FIT). A 20-year lifetime for all investments in 2013-2021

implies FIT payments in the period 2012–2040. The FIT rates for each technology are assumed to exactly reflect, at any point in time, the technology’s levelized cost of electricity (LCOE) (Waissbein et al., 2013):

$$LCOE_{i,t} = \frac{SE * INV_i + \sum_{\tau=0}^T \frac{OPEX_{i,t} + CD_{i,t} - TR * (OPEX_{i,t} + IE_{i,t} + DP_{i,t})}{(1 + ROE)^\tau}}{(1 - TR) * \sum_{\tau=0}^T \frac{P_{i,t} * CF_{i,t} * 8760h}{(1 + ROE)^\tau}}$$

An equity investor perspective was adopted by modeling the cash flows generated for every technology on a single plant basis (Dinica, 2006). The determinants of the LCOE of a technology i in year t are thus the share of equity (SE), the total investment cost (INV), the operational expenses (OPEX), including operation, maintenance and fuel cost, and the cost of debt (CD), which includes the interest expenses and capital payments of the debt-financed investment share in a fixed-rate, 10-year loan. A fixed corporate tax rate (TR) was assumed to apply to all income minus OPEX, interest expenses (IE) and annual depreciation (DP). The annual revenues from electricity generation are determined from the net electric capacity (P) and the time- and technology-specific capacity factor (CF; see below). ROE is the after-tax return on equity that an investor requires taking into account the risk-free rate as well as political, market and technology risks in the designated location. For system integration cost of variable renewable energy technologies (PV, CSP and wind), we considered an additional average of 0.0115 USD/kWh to account for balancing and grid integration cost (IEA, 2008). Table 3 and Table 6 in the appendix provide an overview over the input parameters for renewable energy technologies and key sector-wide assumptions used in our model.

4.2.3. Local and Global Learning

The cost of renewable electricity is assumed to decrease over time as technological capabilities accumulate in the industry (compare Section 2). In particular, the initial investment cost and the fixed O&M cost of technology I were modeled as a function of local and global cumulative installations (Y_{local} and Y_{global}), learning rates and diffusion over time:

$$(iii) \quad INV_{i,t} = \alpha_{i,local} * INV_{i,t-1} * \left(\frac{Y_{i,local,t-1}}{Y_{i,local,t-2}} \right)^{\frac{\ln(1-LR_{i,local})}{\ln 2}} + \alpha_{i,global} * INV_{i,t-1} * \left(\frac{Y_{i,global,t-1}}{Y_{i,global,t-2}} \right)^{\frac{\ln(1-LR_{i,global})}{\ln 2}} \left[\frac{USD}{kW} \right]$$

$$(iv) \quad O\&M \ cost_{i,t} = \beta_i * INV_{i,t} \left[\frac{USD}{kWh} \right]$$

To separate the effects of local and global technological learning, we split up the investment cost into locally and globally sourced components ($\alpha_{i,local}$ and $\alpha_{i,global}$). The learning rate LR, too, is differentiated for local and global learning ($LR_{,local}$ and $LR_{,global}$) (Hayward and Graham, 2013).

The cost structures of different renewable technologies were taken from the literature (sources listed in Table 1). The estimates for the share and type of locally sourced components are based on a survey of news reports on renewable energy projects implemented in Thailand and interviews with local renewable energy investors. In the news report analysis, we coded the companies and main components involved renewable projects in Thailand (such as the Mae Chan PV project shown in Figure 4) according to the type of service or component they provided and the location of business (domestic / international)⁴⁸. The interviews were used to verify the findings about the general patterns of locally sourced components. The information on typical sourcing strategies was then linked to the technology-specific cost structure data to obtain estimates of local and foreign cost shares, to which we applied local and global learning rates obtained from the literature (see Table 1).

In the initial specification, our model used high but realistic estimates for the local share, as presented in Table 1. For all six considered renewable technologies, we assumed that grid connection, EPC (engineering, procurement and construction) and heavy, bulky components are sourced locally, while the core of the electro-mechanical conversion system is sourced globally. This rule leads to very different local shares: from 43% in the case of PV up to 87% for micro hydro. To assess the sensitivity to these assumptions, a second set of model specifications (see section 4.3) uses more pessimistic estimates for local private sector participation (values given in Table 5 in the appendix). A third set of model specifications assumes a cost markup of 20% for all local components in wind, solar PV and CSP, which are relatively new technologies in Thailand.

⁴⁸ We considered local manufacturing as local sourcing, even when it is the result of foreign direct investment.

Table 1: Split between locally and globally sourced components by technology

Technology	Locally sourced parts	Globally sourced parts	Cost split local/global	Learning rate local/global
Wind	Grid connection; engineering; procurement & construction; foundation; rotor blades; tower	Nacelle (including electrical machinery, power electronics & control system)	67%/33% ^a	11.3/4.3 ^e
PV	Grid connection; engineering; procurement & construction; balance of system excluding inverter	PV modules; inverter	43%/57% ^b	17/20 ^e
CSP (solar tower) ^f	Grid connection; engineering; procurement & construction; solar field	Power block; heat transfer fluid cycle	67%/33% ^b	14.6/14.6 ^e
Biomass (anaerobic digestion) ^f	Grid connection; engineering, procurement & construction; fuel shredder; boiler; heat exchanger; piping	Steam turbine and electric generator (prime mover); flue gas and water treatment	75%/25% ^c	5/5 ^d
Biogas	Grid connection; engineering, procurement & construction; fuel handling; balance of system; 75% of converter system	Gas engine (prime mover); 25% of converter system	78%/22% ^d	5/5 ^d
Micro hydro	Grid connection; engineering, procurement & construction; 50% of electro-mechanical equipment	50% of electro-mechanical equipment	87%/13% ^c	5/5 ^d

^aIRENA (2012b); ^bNREL (2012); ^cDelivand et al. (2011); ^dMott McDonald (2011); ^eHayward & Graham (2013); ^fFor both CSP and biomass a range of technological options exists, of which we chose one each to simplify the model; we chose anaerobic digestion because it is the dominant technology in Thailand (JIE, 2008), and solar tower because it represents 43% of the global near-term project pipeline (Hering, 2012).

4.3. Model Specification and Scenarios

Different model specifications were created to evaluate the learning effects, to gauge the impact of key assumptions, and to compare learning effects to other policy priority areas (see Table 2). Models A-L were specified to investigate the impacts of local and global learning. The first four, A-D, assume the local shares estimated in Table 1 and only differ by the learning rates. Model A assumes no learning at all (learning rates set to zero) and serves as base-case scenario, while model B and C estimate the separate effects of local and global learning, respectively, and model D estimates the full joint effect of local and global learning. Models E, F, G and H follow the specifications of models A-D, but use a more conservative estimate of the share of local components (values are given in Table 5 in the Appendix). The models I, J, K and L, too, mirror models A-D, but account for the uncertainty about the initial cost of locally produced components by assuming a markup of 20%⁴⁹ on all local

⁴⁹ The mark-up of 20% is within the range of mark-ups implicitly assumed in policies such as Turkey's Renewable Energy Law 2010 (IEA and IRENA, 2013).

components in wind, solar PV and concentrating solar power. Finally, model GL assumes that no components are locally sourced and global learning opportunities are fully exploited.

The last two models, CARBON and FINANCE, were specified to allow a comparison of the magnitude of learning effects to those of other suggested policy priority areas for international support. In model CARBON, we assumed a global carbon price of USD 15 to reflect a reinvigorated global carbon market from which renewables projects can raise additional financing. Model FINANCE assumes that both debt and equity cost are reduced by one percentage point to estimate the impact of improving financing conditions through policies that reduce investor risks.

Table 2: Model description and specification; all models assume local diffusion of renewable technologies according to AEDP targets and global diffusion according to predictions in IEA (2013b)^a.

Model	Description	Implementation	Purpose
A or basecase	AEDP targets implemented, but neither local nor global diffusion leads to learning	Learning rates LR_{local} and LR_{global} set to 0	Estimate cost without learning
B	Same as A, but local industry realizes learning opportunities from diffusion	$LR_{local} > 0$; $LR_{global} = 0$	Estimate effects of local learning
C	Same as A, but global industry realizes learning opportunities from diffusion	$LR_{local} = 0$; $LR_{global} > 0$	Estimate effects of global learning
D	Same as A, both local and global industries realize learning opportunities from diffusion	LR_{local} and $LR_{global} > 0$	Estimate full effects of learning
E, F, G, H	Same as A-D, but lower share of local components	Reduced local share; values in Table 5 in the Appendix	Estimate sensitivity to share of local cost; account for variance between projects
I, J, K, L	Same as A-D, but cost markup for local components technologies that are new to Thailand	20% cost markup for local components in wind, PV, CSP	Estimate sensitivity to initial local component cost; account for uncertainty about initial cost
GL	Same as C, but no local content	No local content; $LR_{global} > 0$	Evaluate value of local component sourcing
CARBON	Same as A, but renewables projects benefit from carbon credit sales	$LR_{local} = 0$; $LR_{global} = 0$; carbon price USD 15 for 10 years; credits generated according to methodology of Clean Development Mechanism	Compare learning effects to impact of a functioning global carbon market
FINANCE	Same as A, but renewables projects benefit reduced financing cost	$LR_{local} = 0$; $LR_{global} = 0$; the investor's expected rate of return and the lending rate for renewables are reduced by 1%-point	Compare learning effects to impact of derisking activities

^aLocal installation data for 2012 from DEDE (2013); global installations in 2011 for solar, CSP and wind from IEA (2013b); for biomass and biogas from IRENA (2012c); and for micro hydro from IRENA (2012d).

5. Results

5.1. Impact on the Electricity Mix

Our model predicts that, if the AEDP targets are achieved, Thailand will increase its share of non-large-hydro renewables in the electricity sector from 6 to 24%, as shown in Figure 6. Biomass (47%) and biogas (36%) are responsible for most of this increase, given their high capacity increases and high plant utilization. Solar PV and wind contribute 8% and 7%, respectively, while CSP and micro hydro each produce 1%.

Increasing by a total of over 11 GW, the diffusion of renewable energy reduces the pressure to install new conventional power plants. The construction of some coal power plants will be delayed – the capacity in 2021 is 800 MW lower with the AEDP targets implemented – but the most significant effect is on natural gas. In 2021, the installed capacity is 3,600 MW lower than in the case without additional renewable capacity; this leads to a drop of natural gas in the fuel mix from 59 to 46% (see Figure 6b). If all construction delays caused by the diffusion of renewables in the modeled period 2013-2040 are aggregated and stated in MW-years (MWA), natural gas power plants are delayed by 62,250 MWA; coal power plants by 8,850 MWA; nuclear by 8,000 MWA and diesel plants by 1,250 MWA. In terms of displaced electricity, too, natural gas is affected most (654 TWh in 2013-2040), followed by coal (145 TWh), nuclear (90 TWh), lignite (61 TWh) and diesel (5 TWh). In total, our model estimates that the AEDP targets avoid a total of 956 TWh of conventional electricity and 455.7 million tons of CO₂.

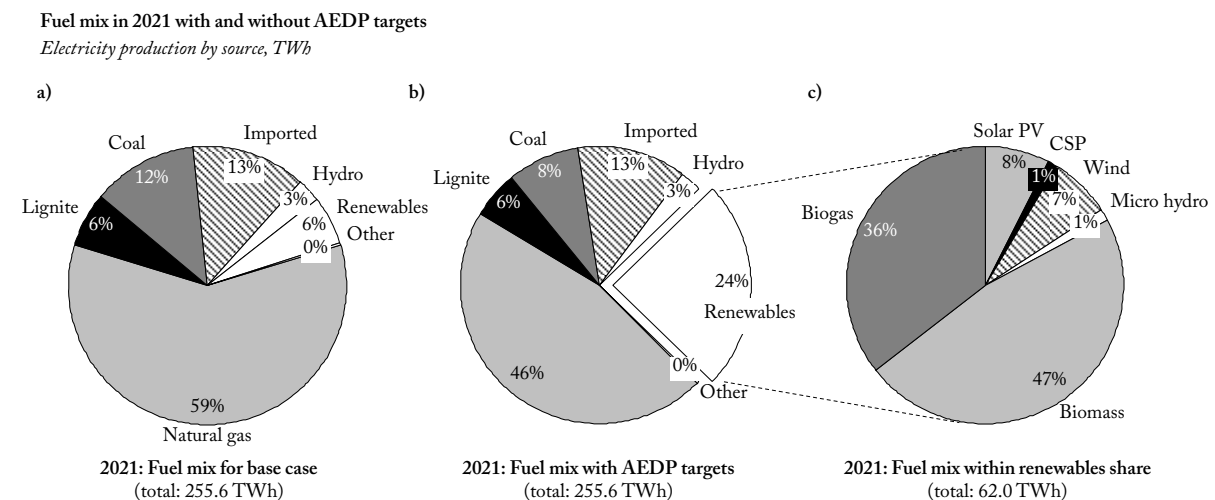


Figure 6: Impact of the AEDP targets on the fuel mix in the electricity sector in 2021.

5.2. Incremental Policy Cost and Effects of Learning

Since we are assuming fixed feed-in tariff payments over a 20-year lifetime for each installation, the cost of the increase in renewable electricity is spread over the period 2013–2040. The annual payments increase linearly with the capacity additions in 2013–2021 to a maximum of almost USD 5bn per year, staying flat until the first added plants retire in 2032 and then dropping to zero (as shown in Figure 7). The savings from avoided conventional electricity production follow a similar path, with small variations between years caused by the delay of large fossil plants.

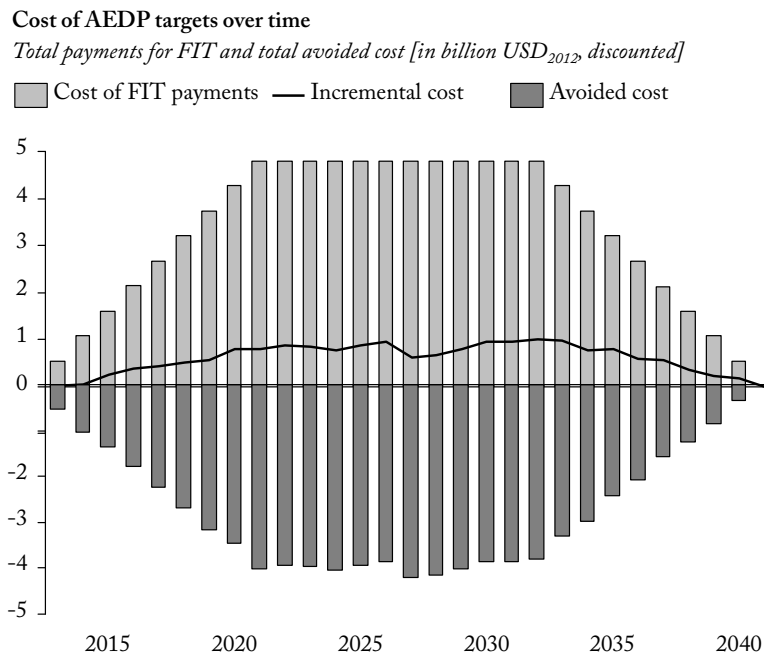


Figure 7: Payments for renewable electricity under the AEDP and avoided fossil electricity over time.

The total cost of reaching the AEDP targets as well as the model’s two main outcome metrics, the (discounted) incremental policy cost and the carbon mitigation cost, are depicted in Figure 8 for the different learning scenarios. For the base case, the FIT payments supporting the renewable energy installations add up to a total of USD \$74.75bn in 2013–2040, while the cost of the avoided conventional electricity reach an aggregate of \$61.43bn over the same period. The remaining,

incremental policy cost is thus \$13.3bn, which corresponds to a mitigation cost of \$29.2 per ton of CO₂.⁵⁰

By exploiting the local and global learning effects, this incremental policy cost can be reduced significantly. If both learning effects are fully exploited in the standard specification of the model (model D), the incremental policy cost drops by about 80% to \$2.6bn. If most components are sourced globally (model H), the effect is less strong, but the cost is still reduced by \$8.8bn (66%) to \$4.5bn. Through learning, the incremental cost falls below the original base-case cost to \$4bn, even if initial cost is assumed to include a 20% markup for local components. The models CARBON and FINANCE, not shown in Figure 8, help put the learning effects in perspective: A \$15 carbon price would reduce incremental cost from \$13.3bn to \$7.52bn, while a reduction of one percentage point in the weighted cost of capital would reduce it to \$9.88bn.

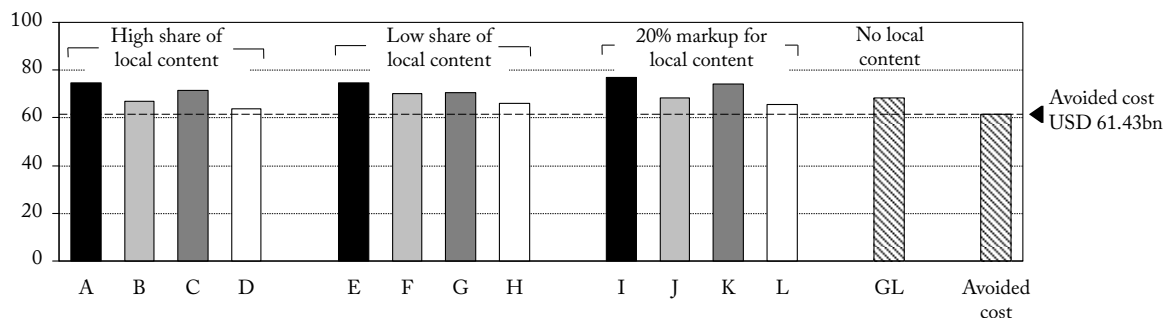
Across all models, the effect of local learning outweighs that of global learning. Figure 8 shows the results for incremental and mitigation cost of all 12 different learning scenarios. If a high share of local sourcing is assumed (models B-D), local learning can reduce the incremental cost by \$6.7bn, while global learning can further decrease them by \$3bn. This strong effect of local learning is robust across all considered model specifications. In the models that assume a low local component share (E-H), local and global learning reduces the incremental cost by 36% and 31%, or \$4.7bn and \$4.1bn, respectively. When a mark-up of 20% is considered (models I-L), local learning shaves 47% (\$8.5bn) off the incremental cost, while local learning reduces them by 19% (\$3bn).

⁵⁰ If distributed as a surcharge on the electricity bill, these incremental cost would peak at about c\$0.3 per kWh in 2020, or about 3% of the average retail electricity price (Ruangrong, 2012).

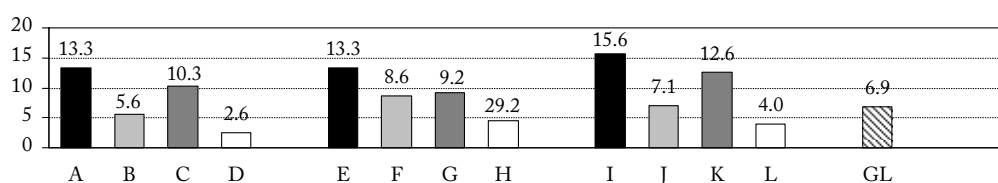
Cost of AEDP targets in different models

No learning
 Local learning
 Global learning
 Local and global learning

a) Total feed-in tariff payments for renewable electricity 2013-2040 [in billion USD 2012, discounted]



b) Incremental cost [in billion USD₂₀₁₂]



c) Mitigation cost [in USD₂₀₁₂ per ton of CO_{2-eq}]

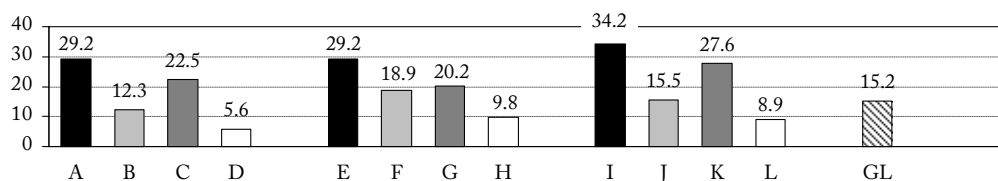


Figure 8: Total cost of supporting the AEDP targets in 2021 in different learning scenarios.

Another important finding is that strong local private sector participation, represented in the models by a high share of local components, can reduce mitigation cost beyond the reductions possible under a purely global value chain. This can be seen when comparing model GL with models D, H and L – the incremental cost in all three models are significantly lower than in GL. Indeed, the effect of local learning alone exceeds the total learning effect in GL in all but model F, the model with a low share of local content.

5.3. Differences between Technologies

The effects seen on the global level are more nuanced when looking at the effects by technology. Figure 9 shows the LCOE of all technologies in 2021 for different scenarios. It can be seen that, overall, the learning effect is strongest for CSP (-54%) and PV (-43%) and weakest for micro hydro (-8%) and biomass (-3%). Similar differences are visible for the relative importance of local and global learning. The effect of local learning is much stronger for CSP, with 41% and 13% reduction,

respectively, whereas global learning is more relevant for PV (25% compared to 18%). Local learning also outweighs global learning for wind, biogas and micro hydro. However, in biomass, both are not very significant.

Levelized cost of renewable electricity in 2021 in different models

LCOE for [in cUSD₂₀₁₂ per kWh]

■ No learning (model A) ■ Local learning (B) ■ Global learning (C) □ Local and global learning (D)

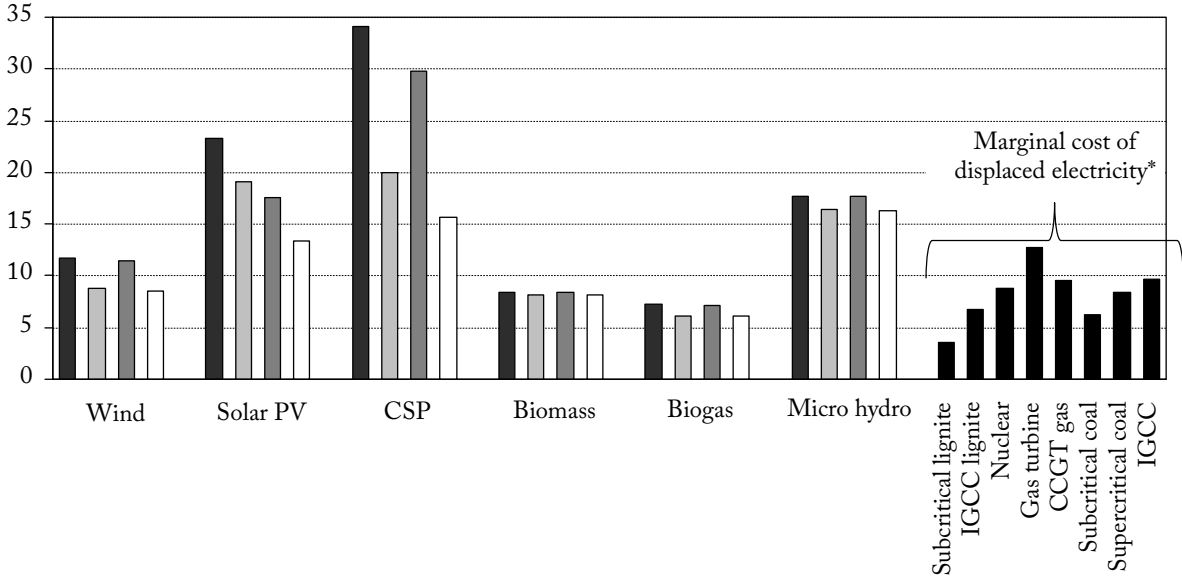


Figure 9: Effect of technological learning on the levelized cost of different renewable energy technologies in 2021. *The presented cost for fossil fuel electricity represents marginal cost of newly built power plants; the fuel cost reflect import prices of coal, diesel and natural gas (see Table 4 in the attachment).

6. Discussion

6.1. How to Tap Local Learning Potentials

The climate policy regime that emerges for the post-2020 period foresees that developing countries will pursue domestic policies that deliver on both climate and development objectives. In the view of national governments, local private sector participation in the value chains of low carbon investments holds the promise of creating employment and growth opportunities. At the same time, as our model results suggest, it can help to reduce the long-term cost of emissions mitigation. The process linking these two objectives is *local technological learning*. Our calculations imply that local learning can reduce the cost of renewable electricity to the point where they are very close to competitiveness with fossil fuels. But how can developing countries realize the learning opportunities that our model predicts are

possible? And how can the international institutional framework assist developing countries in this agenda?

Our case study of Thailand's electricity sector highlights that the cost reduction opportunities from local learning depend on three interlinked factors: the (cumulative) local installations at the beginning of the analyzed period, which can be understood as proxy for the maturity of the domestic industry; the average share of locally sourced components; and the rate of local learning in the different technologies.

First and foremost, the potential for future cost reductions from technological learning is determined by the (cumulative) size of the existing domestic market. The projected learning potentials in our model are highest for technologies that are new to Thailand, such as solar PV and CSP, while mature industries, such as biomass, exhibit limited opportunities to radically alter the cost structure of future investments.

The share of local components, the second factor, depends crucially on the *availability* of local components, which in turn depends on the amount of prior local investment in building up production capacity by firms along the industry chain. Any such investment will hinge on a credible, long-term market perspective (Pueyo et al., 2011). But besides their availability, the share of locally sourced components also depends on their *competitiveness*. Research has presented ample evidence that the competitiveness of local firms is the result not only of factor cost, or hardware imports, but also their stock of technological capabilities (Bell and Figueiredo, 2012). Without the necessary capabilities – i.e., if the initial markup is too high – local firms might never be able to enter the virtuous cycle of learning and new investments. Even if the investment comes from foreign firms, it will require complementary local capabilities to be “absorbed” effectively (Bell, 2010). Local technological capabilities depend on domestic private and public investments, in the form of a skilled workforce, local science and technology infrastructure, as well as firm networks and coordinating actors. International factors, such as the conditions for access to state-of-the-art technology, also play an important role for the local private sector to produce competitive products and services.

Lastly, the third and most important factor in our model that determines the potential for learning to reduce cost compared to the base case is the *rate of learning*. If the learning opportunities are not seized, a large share of locally sourced components does not yield any benefit in terms of mitigation cost. Indeed, if there is a positive markup, it might actually be counterproductive, at least from a cost perspective. The extent to which industries can reap the benefits of learning is determined by the

opportunities to *create* new knowledge from experience, but also by the processes that govern the dissemination, utilization and retention of the created knowledge (Bell and Albu, 1999). These processes can be shaped and enhanced by domestic governments and international support mechanisms.

6.2. Implications for Domestic Policy

Our results suggest that the governments of developing countries should pursue any investments in low carbon infrastructure with the explicit target of seizing the opportunity to build up local technological capabilities. First and foremost, whether low carbon investments can promote learning is determined by the nature of the policies that attract this investment. Experience in developed countries has shown that technological capabilities can best be created under stable and predictable market conditions (IRENA, 2013). Developing countries can create such conditions domestically through long-term targets and stable regulatory frameworks, as well as a clear allocation of responsibilities in the public sector. Options to promote industry-wide learning through efforts targeted at the dissemination, utilization and retention of created knowledge include investments in collaborative research programs that accompany and monitor infrastructure technology; public institutions for testing and certifying technology; requirements for beneficiaries of government support to publish non-sensitive information on cost and performance of the technologies; and the creation of government-led platforms for knowledge exchange.

Apart from the need for efforts targeted at learning, the case study also suggests that policies to subsidize early local private sector participation can be a good investment. By lowering entry barriers in the beginning, public support can create conditions that enable learning, which, in the long term, lowers overall cost beyond what would have been possible with purely foreign suppliers. But such a policy needs to be designed with a clear target and procedure to review and eventually phase out support. Furthermore, direct subsidies for local sourcing of specific components carry the risk of wasting public resources on subsidizing the production of components that are too costly, or too complex, to yield any local learning effects. Nevertheless, if they are focused on technologies and components for which technical expertise is available (or attainable), and if they are linked to efforts to build technological capabilities, our model suggests that local content policies can deliver on both development and cost reduction objectives (see also Johnson, 2013).

6.3. Implications for International Technology Support Mechanisms

In its support for technology development and transfer, the international climate policy regime has recently shifted attention from global agreements toward country-specific support and from the transfer of hardware to the build-up of local technological capabilities. Most notably, the Technology Mechanism (TM) was created under the UNFCCC in 2011 to determine “technology needs [...] based on national circumstances and priorities”, and to “accelerate action consistent with international obligations, at different stages of the technology cycle, including research and development, demonstration, deployment, diffusion and transfer of technology in support of action on mitigation and adaptation” (UNFCCC, 2011, p. 18-19). By emphasizing local and global aspects of technology development, innovation, and knowledge networks, the TM’s functions clearly go beyond the ‘one-size-fits-all’ approach of the mechanisms under the Kyoto Protocol, but also beyond the purely country-centered practice of technology needs assessments supported by the United Nations. However, given the range of initiatives that institutions such as the TM could potentially support means that there is a need for analysis to inform the design and priority setting of these institutions. The analysis presented in this paper provides implications for the allocation of resources between global and local support.

Our results suggest technology characteristics, such as novelty and the share of simple, heavy and country-specific components, determine the relevance of local learning in concert with country characteristics, such as the existence of domestic industry in similar sectors and the size of the already existing market for the considered technology. These case-specific differences suggest that the TM should ideally integrate global and local perspectives. In cases where local learning is crucial, the TM should assist countries by strengthening the local innovation system, e.g., by identifying technology needs and priorities; by supporting the design of policies and regulations; by providing training and capacity building; through efforts to provide developing countries with access to IPR; or through the creation of local actor networks. In cases where global learning is very important, the TM should strengthen the global, sectoral innovation systems through the creation of global technology roadmaps; the promotion of global technology standards; the coordination of policies across countries and regions; the creation of global, technology-centered networks; or the coordination of institutional linkages between the TM and other global and regional institutions (such as the World Trade Organization, the Green Climate Fund, or the Global Environmental Facility). Overall, our case study suggests that the recent emphasis on *local* capabilities is promising. However, since resources are necessarily limited,

the TM should pursue these different activities with priorities reflecting country characteristics and technology-specific value chain structures.

6.4. Limitations

Quantitative case studies such as the one presented in this paper have a number of inherent limitations that constrain the validity and applicability of our findings. We see three main factors that need to be highlighted here. First, we are not aware of any other attempt to differentiate local and global learning in a techno-economic model for a developing country. Our projections for the potential of local learning are therefore limited by the availability of empirically grounded, cross-industry estimates for local component shares, cost mark-ups and local learning rates.⁵¹ To obtain more accurate estimates than those presented here, further research is needed to better understand the cost structure and cost dynamics of renewable energy projects in developing countries. A second limitation concerns the model's output metrics. Government decisions should be made based on cost-benefit calculations. Our paper provided only estimates for possible cost reductions – the benefits side – while neglecting the cost of policies to realize and support local learning processes. Public research programs, testing and certification institutions, and international support for policy design and capacity building all come at a cost. In order to provide estimates for the *leverage* of these public investments, i.e., how many cost reductions can be realized at what cost, further data and analysis is necessary. This is particularly important when comparing different policy options. Lastly, by modeling technological capabilities as production cost, and modeling technological learning as cost reductions through a logarithmic function of only installations, our model grossly simplified what is, in reality, a set of extremely complex and distributed processes with multiple qualitative and quantitative dimensions. It can thus only function as a small piece in the broader set of analyses on technological learning that aims to support the design of domestic and international climate policy.

⁵¹ For example, we were only able to obtain differentiated estimates for local and global learning rates for wind and solar PV, and for both cases the numbers are from developed country analyses.

7. Conclusion

This paper presented a case study of Thailand's electricity sector in order to estimate the effects of local and global technological learning on the cost of renewable energy technologies in developing countries. Our model results suggest (i) that technological learning can, in the near future, reduce the cost of renewable electricity in emerging economies to a level that is close to competitiveness with fossil fuels; (ii) the major potential for cost reductions through learning lies in the build-up of *local* technological capabilities; and (iii) the relative importance of local and global learning, while clear in aggregate terms, differs significantly between technologies. This finding lends quantitative support to the argument that the conditions enabling local learning, such as a skilled workforce, a stable regulatory framework, and the establishment of sustainable business models, have a more significant impact on the cost of renewable energy in developing countries than global technology learning curves. The recent shift of international support under the UNFCCC toward the strengthening of local innovation systems is therefore promising. However, our results also suggests that international support must not disregard the global innovation system perspective in order to reap the full benefits of technological learning across the wide range of clean technologies. These insights are particularly relevant for the ongoing design and functional specification of mechanisms for technology support under the post-Kyoto climate policy regime of the UNFCCC. Here, our quantitative approach and the focus on mitigation cost complements existing qualitative and conceptual work on the topic. Further qualitative research should explore in more detail the economics of renewable energy projects in developing countries, and the effectiveness of different policy options to promote technological learning in and across the developed world. Additional quantitative research should investigate the leverage of different policy options, in particular the relative merit of options targeted at learning, de-risking and global pricing of carbon emissions.

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Appendix A: Cost of Avoided Electricity

Fuel Mix in the Electricity Sector

Thailand's electricity sector is partly vertically integrated and dominated by state-owned enterprises (Wisuttisak, 2012). The Electricity Generation Authority of Thailand (EGAT) is the transmission system operator and directly operates around 50% of the generation assets and, as their largest shareholder, controls the two largest independent power producers. Furthermore, the wholesale market is not liberalized. Decisions over new power plant investments are therefore still made based on long-term integrated plans, rather than purely based on market signals, and plant utilization is based on long-term allocations rather than marginal cost of generation.

Our model of the fuel mix aims to reflect this decision-making process. We took the power plant pipeline from the Power Development Plan from June 2012 (EPPO, 2012a) and assumed that all hydropower, combined-heat-and-power, and contracted import capacity comes online as planned. Additional power plants were assumed to be built, in the sequence determined by the plan, whenever dependable capacity exceeds peak demand by less than 15%, or total expected demand exceeds expected generation, based on historic capacity factors, exceeds more than 5%. This approach is similar to the one adopted by domestic researchers (Sangarasri-Greacen and Greacen, 2012). The dependable capacity equals the total capacity adjusted by factors that aim to reflect the fact that not all build capacity can be expected to be available in the moment of peak demand, because of maintenance, failures, or intermittent generation.⁵² The fuel mix was then calculated, on a yearly basis, from historic capacity factors, marginally adjusted for the dispatchable plant fleet to exactly meet yearly demand. "Dispatchable" refers here to the plants that are ramped up and down to balance demand, i.e., the full fleet excluding renewables, contracted import capacity (lignite and hydro), municipal solid waste and (heat-led) cogeneration.

⁵² The factors are taken from Sangarasri-Greacen and Greacen (2012) and listed in Table 3.

Avoided Electricity

To model the effect of renewable energy diffusion on conventional electricity generation, we compared the hypothetical scenario without renewable energy diffusion to the case of full implementation of the AEDP targets. The total avoided electricity we then calculated by aggregating the differences between total generation in 2012-2041 with and without AEDP targets for each of the dispatchable technologies (generation from non-dispatchable technologies is not affected by the AEDP).

Modeling the marginal cost of avoided electricity required one more step of differentiation. The impact of renewable capacity installations can be twofold: plant utilization of dispatchable power plants can be reduced or the construction of new power plants postponed. Our model accounted for these two effects by dividing the total avoided electricity into build and operating margins. For all displaced electricity the cost of electricity was calculated based on the LCOE approach presented in section 4.2.2. However, in the case of reduced plant utilization, the operating margin, we assumed the marginal cost of electricity to contain only the variable cost (O&M and fuel). The displaced electricity from postponed power plants, the build margin, contains all fixed and variable cost.⁵³ Table 4 summarizes the input assumptions for all conventional technologies.

⁵³ This procedure was also employed by Schmidt et al. (2012) and is related to the rules employed to calculate avoided carbon emissions in the Clean Development Mechanisms under the UNFCCC.

Appendix B: Model Input Assumptions

Table 3: Input assumptions for renewable energy technologies (values for 2012; \$=USD₂₀₁₂)

	Size (MW)	Lifetime [a]	Investment [\$/kW]	O&M fix [\$/kW _a]	O&M variable [\$/MWh]	Fuel cost [\$/MWh]	Efficiency [%]	Capacity factor [%]	Dependable capacity [%]	Carbon credits* [kCO _{2e} /MWh]
Wind	10	20	1,980 ^a	60 ^a	0 ^a	-	-	31.8 ^c	9 ^f	555.4 ^b
PV	10	20	2,830 ^a	50 ^a	0 ^a	-	-	19.8 ^c	20 ^f	555.4 ^b
CSP	5	20	4,910 ^a	50 ^a	0 ^a	-	-	21.5 ^c	70 ^g	555.4 ^b
Biomass	10	20	2,157 ^b	0 ^b	10.4 ^b	41.2 ^b	19.8% ^b	69 ^b	55 ^e	511.3 ^b
Biogas	1	20	2,554 ^c	116 ^c	0 ^c	10 ^c	31% ^c	70 ^c	21 ^g	511.3 ^b
Micro hydro	1	20	2,800 ^d	112 ^d	0 ^d	-	-	29 ⁱ	40 ^g	511.3 ^b

^aNREL (2012); ^bDelivand et al. (2011); ^cPattanapongchai and Limmeechokchai (2011); ^dIRENA (2012e); ^ecalculated based on data from the IRENA Global Atlas (3Tier, 2014); ^fNaksrisuk and Audomvongseree (2013); ^gSangarasri-Greacen and Greacen (2012); ^hMunchareon et al. (2010); ⁱPromjiraprawat and Limmeechokchai (2012) other data are own assumptions and calculations; *used for calculation of generated carbon credits; data from the Thailand Greenhouse Gas Management Organization (Munchareon et al., 2010), which calculates the avoided carbon emissions of renewable projects in Thailand based on CDM methodology. The CDM methodology distinguishes between intermittent (solar and wind) and non-intermittent technologies (biomass, biogas and micro-hydro)- Because they need back-up power, intermittent sources are assumed to not much affect the decision about new fossil-fuelled power plants. The electricity they avoid therefore comes mostly from existing power plants (75% to 25%), while non-intermittent sources are assumed to avoid a larger amount of newly built fossil-fuelled power capacity (50% to 50%). Since the new power plants have lower emissions than the existing plant fleet, the intermittent sources end up avoiding slightly more carbon emissions than the non-intermittent sources.

Table 4: Input assumptions for dispatchable fossil fuel technologies (values for 2012; \$=USD₂₀₁₂)

	Lifetime [a]	Investment [\$/kW]	O&M fixed [\$/kW _a]	O&M variable [\$/MWh]	Fuel efficiency [%]	Fuel cost* [\$/kWh]	Capacity factor [%]	Carbon emissions [tCO _{2e} /MWh]
Subcritic. lignite	30	1,125 ^a	38.91 ^b	11.02 ^b	35 ^b	0.005 ^d	90	1,159 ^b
IGCC lignite	30	2,830 ^c	50 ^c	7.9 ^c	46 ^c	0.005 ^d	90	882
Adv. nuclear	40	5,429 ^c	91.65 ^c	2.1 ^c	33 ^c	0.003 ^d	90	21 ^b
Gas turbine	**	**	7.21 ^c	15.28 ^c	31.4 ^c	0.052 ^c	30	631 ^b
CCGT	30	1,006 ^c	15.1 ^c	3.21 ^c	54 ^c	0.052 ^c	60	404 ^b
Subcritic. coal	**	**	38 ^b	0.04 ^b	36 ^b	0.015 ^f	90	973 ^b
Supercrit. coal	30	2,934 ^c	31.18 ^d	4.7 ^d	39 ^c	0.015 ^f	90	782 ^b
IGCC coal	30	3,784 ^c	51.39 ^c	8.45 ^c	39 ^c	0.015 ^f	90	782 ^b
Diesel turbine	**	**	12 ^a	28.6 ^a	22 ^a	0.061 ^d	30	808 ^b

CCGT: combined cycle gas turbine; IGCC: integrated gasification combined cycle; ^aPattanapongchai and Limmeechokchai (2011); ^bPromjiraprawat and Limmeechokchai (2012); ^cDOE/EIA (2013); ^dEPPO (2012d); ^eprice for natural gas is for imports from Myanmar, from PTIT (2012); ^fIEA (2013c); *Fuel price trends from IEA (2013c); **Not needed because no new power plants in the pipeline

Table 5: Split between locally and globally sourced components by technology in models E-H, representing a low share of local components

Technology	Locally sourced parts	Globally sourced parts	Cost split local/global	Learning rate local/global
Wind	Grid connection; engineering; procurement & construction	Nacelle (including electrical machinery, power electronics & control system); foundation; rotor blades; tower	36/64 ^a	11.3/4.3 ^d
PV	Grid connection; engineering; procurement & construction	PV modules; inverter; balance of system	36/64 ^b	17/20 ^d
CSP	Grid connection; engineering; procurement & construction	Power block; heat transfer fluid cycle; solar field	23/77 ^b	14.6/14.6 ^d
Biomass	Grid connection; engineering, procurement & construction; fuel shredder; piping	Steam turbine and electric generator (prime mover); flue gas and water treatment; boiler; heat exchanger	37/63 ^c	5/5 ^c
Biogas	Grid connection; engineering, procurement & construction; fuel handling	Gas engine (prime mover); converter system; electrical system	48/52 ^c	5/5 ^c
Micro hydro	Grid connection; engineering, procurement & construction	Electro-mechanical equipment	77/23 ^c	5/5 ^c

^aIRENA (2012c); ^bNREL (2012); ^cMott McDonald (2011); ^dHayward & Graham (2013).

Table 6: Sectoral assumptions in the model

Factor	Assumption	Source
Currency	USD 2012 in real terms	---
Exchange rate	1 USD = 31.5 Thai Baht	The World Bank
Inflation	2.5%	Bank of Thailand
Equity/debt split	30/70	Current practice
Return on equity	11.2% real	UNFCCC (2010)
Lending rate	6.7% nominal	Ondraczek et al. (2013)
Loan tenor	Half of investment lifetime	Waissbein et al. (2013)
Tax rate	30%	Current practice
Depreciation	Linear, max 5% p.a., min book value 5%	Current practice
Discounting of public expenditures	Equals 40-year bond yield of 4.43 %	Thai Bond Market Association, http://www.thaibma.or.th/yieldcurve/YieldTTM.aspx ;; assessed on 4/3/2014

Compulsive Policy-Making – The Evolution of the German Feed-in Tariff System for Solar Photovoltaic Power[¥]

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Abstract

In recent years, policy approaches that build upon the notion of innovation systems have enjoyed increasing attention in science, technology and innovation policy. But while the usefulness of systemic thinking in policy-making has been demonstrated in a large number of empirical settings, we still lack a detailed understanding of the dynamics at play when policy makers address systemic problems. In this paper, we show how complex interdependencies and the uncertain nature of technological change shape the process of targeted policy interventions in socio-technical systems. Towards this end we analyzed the evolution of the German feed-in tariff (FIT) system for solar photovoltaic power, a highly effective and widely copied policy instrument targeted at fostering the diffusion and development of renewable energy technologies. We find that the policy has been subject to a considerable amount of changes, many of which are the result of policy makers addressing specific system issues and bottlenecks. Interestingly, however, often these issues themselves were driven by unforeseen technological developments induced by previous policy interventions. We argue that the pattern of policy serving as both a solution to and a driver of technological bottlenecks shows strong similarities with what Rosenberg (1969) called ‘compulsive sequences’ in the development of technical systems. By shedding more light on how the characteristics of socio-technical systems affect policy interventions, our framework represents a first step towards more closely integrating the literature on innovation systems with the work on policy learning.

Keywords: Sustainability transitions, Innovation system, Innovation policy, Policy learning, Feed-in tariff, Solar photovoltaic power

Highlights:

- We study how technology dynamics and uncertainty affect policy interventions in innovation systems.
- We investigate the German feed-in tariff system for solar photovoltaic power.
- We show that technological change was both a result and driver of policy changes.
- We point to parallels in the process with Rosenberg's (1969) 'compulsive sequences'.
- Our research more closely integrates the literature on innovation systems and policy learning.

1. Introduction

Environmental degradation, resource depletion and climate change are pressing societal problems that call for a redirection of economic growth towards a more environmentally sustainable pathway (UNEP, 2011). Such a ‘sustainability transition’ is likely to require the development and use of fundamentally new products, processes and services (Markard et al., 2012; Smith et al., 2010). Whereas this implies an altered behavior of a wide range of actors, such as corporations and private consumers, there is a broad consensus that public policy will have to play an important part in facilitating the transition. Considering the urgency of problems, it is argued that regulators should guide and accelerate the process of change by altering the institutional framework, breaking path dependencies and fostering the emergence of innovative, more environmentally benign technologies (Jacobsson and Bergek, 2011; Unruh, 2002).

In recent years, innovation scholars have strongly advanced our understanding of the role that public policy can play in fostering the transition towards sustainability. For example, the literature on innovation systems has identified so-called ‘system failures’ or ‘system problems’ that hinder the development and diffusion of new technologies (e.g., Klein Woolthuis et al., 2005; Negro et al., 2012) and has suggested a number of ‘functions’ or ‘key processes’ policy makers should support to overcome these issues (e.g., Bergek et al., 2008; Edquist, 2011; Hekkert et al., 2007). The practice of systems thinking has found increasing use in policy circles in recent years (Wieczorek and Hekkert, 2012). Up to this point, however, we lack a detailed understanding of how policy responses emerge from systemic imbalances and how they co-evolve with the system that policy makers intervene in (Kuhlmann et al., 2010). The literature emphasizes the complex nature of innovation systems, with many interdependent actors and institutions (Faber and Alkemade, 2011). Yet, it remains unclear how this affects policy maker’s ability to purposefully induce technological change. Studies in the field of policy sciences have stressed the emergent nature of policy processes and investigated factors that facilitate policy learning (Lindblom, 1959). However, when analyzing the drivers of policy evolution, typically these studies have focused on the political system as the intervening entity, rather than technological change and the characteristics of the system to be intervened in.

To gain more insights into the dynamics that result when policy makers try to purposefully intervene in socio-technical systems, in this paper we address the question of *how the complex dynamics of innovation systems shape the process of policy interventions targeted at inducing technological change.*

Towards this end, we study the evolution of the widely copied German feed-in tariff (FIT) system for solar photovoltaic (PV) power as an instrument that has been highly effective in driving the development and diffusion of PV technology. In this context, we analyzed a large number of archival documents pertaining to the policy process such as legislative texts, protocols of parliamentary debates, expert studies and press articles. This archival analysis was complemented by interviews with policymakers and designated PV industry experts as actors in and observers of the policy process.

We show that the German FIT for PV has evolved in a highly iterative way with policy makers adjusting the policy design over time. Some of the policy changes were due to politics and policy makers correcting flaws in previously implemented legislations. More interestingly, however, we find that besides these factors the evolution of the German FIT for PV was strongly driven by – often unforeseen – developments in the technological sphere. Policy makers implemented policies that addressed particularly prevalent ‘system failures’ or ‘system issues’ hindering the development and diffusion of solar PV in Germany. Although these policy measures contributed to eliminating specific issues, we find that, by inducing unexpected technological developments, policy simultaneously contributed to the emergence of new issues which needed to be addressed in subsequent steps. We argue that understanding policy interventions in socio-technical systems in analogy to what Rosenberg (1969) described as ‘compulsive sequences’ of innovation, may help inform future interventions in innovation systems. The framework of ‘compulsive policy-making’ we propose goes beyond more generic frameworks of policy learning (e.g., Bennett and Howlett, 1992; Lindblom, 1959) by stressing the role of technological change and complex interdependencies in socio-technical systems as a driver of policy change.

The remainder of this paper is structured as follows: Section 2 presents a brief overview of the work on innovation systems and discusses potential mechanisms shaping policy dynamics suggested in the literature. Research case and method are outlined in sections 3 and 4. Section 5 describes the evolution of the German FIT system for PV, followed by a discussion of the underlying technological dynamics and the theoretical framework we derive in section 6. We conclude with a brief description of the study’s limitations, suggestions for future research and a summary of the main contributions.

2. Theoretical Perspective

2.1. Innovation Systems Analysis as a Means to Inform Policy Interventions

In the last two decades, the concept of innovation systems has gained increasing importance in informing policy interventions in the field of science, technology and innovation policy (Edquist, 2011; Smits and Kuhlmann, 2004; van Mierlo et al., 2010). It builds upon the idea that the development, diffusion and use of technologies results from the interplay of a large number of actors (e.g. firms, policy makers), networks (formal and informal), technologies (e.g., knowledge and artefacts) and institutions (e.g. norms, values or regulations) within a socio-technical system (Carlsson and Stankiewicz, 1991; Edquist et al., 2005). To foster technological change, the literature suggests carefully analyzing the socio-technical system to identify so-called ‘system failures’ or ‘system problems’ as the focus of policy interventions. Previous work has clustered failures into categories, such as ‘institutional’, ‘network’ or ‘capability’ failures, and suggested systematic procedures for their identification (Carlsson and Jacobsson, 1997; Klein Woolthuis et al., 2005; Negro et al., 2012; Smith, 1999). In the latter context, a number of ‘functions’, ‘key processes’ or ‘key activities’ have been proposed that policy makers should focus on when searching for systemic failures that may prevent technology development and diffusion (Bergek et al., 2008; Edquist, 2011; Hekkert et al., 2007). It is suggested that, to devise technology-specific policies, policy makers should measure the extent to which different processes are present within an innovation system, detect mechanisms inducing or blocking these processes and implement policy measures to remove potential system bottlenecks (Bergek et al., 2008; Wiczorek and Hekkert, 2012).⁵⁴

The analysis of innovation systems has proven a powerful heuristic for identifying starting points of policy interventions and explaining the success or failure of technology development and diffusion. However, since the focus of innovation system studies is on analyzing the socio-technical system as a whole rather than the details of policy processes, we lack a sufficient knowledge about how policy

⁵⁴The logic of identifying and removing system bottlenecks appears similar to ‘Liebig’s law of the minimum’ in agricultural science. According to Liebig’s law, which was originally developed by Carl Sprengel in the early 19th century, the performance of a system consisting of a number of interdependent elements is limited by the scarcest resource.

responses emerge from systemic imbalances and how they co-evolve with the system that policy makers intervene in (Kuhlmann et al., 2010). While the innovation systems literature itself does not intend to provide a detailed explanation of the policy process, a better understanding of the link between system failures and policy-making could be fruitful as it may help to a) uncover the underlying dynamics of innovation system evolution and b) improve the practical relevance of policy recommendations made. Therefore, in the following we take a closer look at two mechanisms affecting the dynamics of policy interventions in innovation systems that have been discussed in the literature.

2.2. Potential Mechanisms Shaping the Dynamics of Policy Interventions in Innovation Systems

As one important mechanism shaping the dynamics of policy interventions in innovation systems, early studies in the field have investigated the role of *politics and interest* (Jacobsson and Bergek, 2004; Jacobsson and Lauber, 2006; Jacobsson et al., 2004). In line with the literature on the politics of sustainability transitions it has been pointed out that the transformation of socio-technical systems is an inherently political process influenced by mindsets, framing and power struggles (Kern, 2011; Meadowcroft, 2009, 2011; Scrase and Smith, 2009). Politicians anchored in an existing regime are unlikely to show strong support for emerging technologies and may resist related political initiatives (Kern and Smith, 2008). Moreover, policy makers may hold differing opinions on what constitute the most important system failures and how to remove them (Meadowcroft, 2009).

A second mechanism that is likely to shape the dynamics of policy interventions aimed at removing specific system failures is *limited capacity and foresight of policy makers*. Even if there is a political consensus regarding the goals and means of policy-making, the inherent complexity of socio-technical systems may limit the degree to which consequences of policy interventions can be accurately foreseen (Faber and Alkemade, 2011). As expressed in Lindblom's (1959) 'science of muddling through', policy makers generally possess limited capacity to enlist and evaluate all possible policy measures and outcomes. As a result, they therefore have to make use of a try-and-error approach to partially achieve their goals and subsequently adjust actions based on the experience they have gained (Forester, 1984; Lindblom, 1959, 1979). The resulting process of policy learning has been an important subject of study in the literature on policy science (Bennett and Howlett, 1992; May, 1992; Sanderson, 2002). In this context, different forms of policy learning have been identified and investigated with regard to their antecedents (Bennett and Howlett, 1992).

The literature on policy learning has generated valuable insights into the exact mechanisms through which policy makers learn. Yet, in this stream of literature the question of what shapes the policy process has generally been answered by looking at the characteristics of governing bodies rather than the properties of the socio-technical system in which they intervene. In particular, iterations in policy processes are usually assumed to emerge due to the inability of policy makers to design appropriate policies. While the political system decisively affects policy learning, it seems promising to take a closer look at how the process of policy learning is affected by the dynamics of and interdependencies within the socio-technical system that policy makers intend to change. Policy learning may play a particularly important role when policy makers try to purposefully induce technological change which has been shown to evolve in a non-linear, unpredictable way. In line with this, the literature on innovation systems stresses that these systems consist of a large number of structural elements that interact through various channels, implying that the outcome of policy measures may be hard to anticipate. Yet, while it has been acknowledged that policy interventions in innovation systems may have unforeseen effects (Bergek and Jacobsson, 2003; Bergek et al., 2008), we currently lack a sufficient understanding of how the complexity of socio-technical systems might relate to processes of policy learning. At present, the literature predominantly assumes positive interdependencies between elements of innovation systems. It is suggested that removing specific system failures leads to ‘virtuous cycles’ (Bergek and Jacobsson, 2003; Hekkert and Negro, 2009; Negro and Hekkert, 2008), ‘cumulative causation’ (Hekkert et al., 2007; Suurs and Hekkert, 2009) and the emergence of ‘positive externalities’ (Bergek et al., 2008). Positive interdependencies have been empirically demonstrated in several case studies (e.g., Suurs and Hekkert, 2009). Yet, one could think of cases where removing system failures may not affect all other system elements in a positive way. For example, fostering demand to overcome ‘market failures’ can lead to the scaling-up of production and lower product costs, thereby raising the barriers to market entry for entrepreneurs (Hoppmann et al., 2013). As a result, complex interdependencies between the elements of an innovation system may lead to situations where policy interventions unexpectedly enhance existing or generate new system failures, requiring policy makers to learn. Considering this possibility, in this paper we focus on the question *how the complex dynamics of socio-technical systems shape the process of policy interventions targeted at inducing technological change*. Based on an in-depth case study of a policy intervention that aims at addressing specific failures in an innovation system, we derive a process model that integrates the different mechanisms presented in this section.

3. Research Case

To gain more insights into the dynamics that result when policy makers try to address failures in socio-technical systems, we study the evolution of the widely-copied German feed-in tariff (FIT) system for solar photovoltaic (PV) power from 1991 to early 2012. FITs, which grant power producers a fixed price per unit of electricity, are generally implemented to foster technological innovation and diffusion of renewable energy technologies (Dewald and Truffer, 2011).⁵⁵ Studying the evolution of this instrument therefore allows us to better understand the dynamics that result when policy makers try to purposefully intervene in an innovation system to enhance its performance.

Germany is a suitable country for the analysis since throughout the period of analysis public and political support in Germany for renewables was rather high.⁵⁶ Compared to other countries, there has been a stronger political consensus that increasing renewable energy supply is desirable, implying that political struggles revolved not so much around the goals (i.e. what to achieve) but the means (i.e. how to achieve them).⁵⁷ Partisan politics thus played a smaller role than in other contexts. Furthermore, we chose Germany as a country since the FIT system has been very effective in increasing the share of renewable power in the electricity mix, and has served as a blueprint for FIT schemes in other countries (Ringel, 2006). Of the more than 60 countries that have introduced a FIT, Germany was the second country to adopt this instrument and up to this point has shown a remarkable continuity in its operation (REN21, 2011). The long time horizon over which developments in the legislation can be tracked was considered advantageous for obtaining robust results.

We further confine our analysis to the case of solar photovoltaic power. While PV bears a large physical potential for the generation of clean electricity, its levelized costs of electricity (LCOE) are

⁵⁵ As will be seen in section 5, motivations to implement a FIT often go beyond the mere development and diffusion of renewable energies. For example, the appendix of the German Renewable Sources Act 2000 lists, among others, the creation of industries and jobs, reduction of import dependence of fossil fuels, as goals.

⁵⁶ We focus on policies and market formation in Germany. Still, we include developments in the innovation system for PV outside of Germany in our analysis whenever they have important effects on the socio-technical system in that country.

⁵⁷ It should be noted that, especially at the end of the 1980s renewables faced significant headwind from the CDU/FDP leadership in the German Bundestag (Jacobsson and Lauber, 2005). Moreover, there remains considerable disagreement regarding the rate at which renewable energy technologies should be deployed.

still well above those for fuel-based electricity sources. As a result, PV currently is strongly dependent on policy support, implying a high visibility of policy effects and policy dynamics in the socio-technical system (Peters et al., 2012). The good opportunity to observe policy dynamics in operation militates in favor of choosing PV as a unit of analysis.⁵⁸

Finally, we set the temporal boundaries of our research to the time from 1991 to the beginning of 2012. We constrain our analysis to the German Renewable Energy Sources Act of 2000 and its subsequent amendments because the first version of the German FIT, the so-called ‘Stromeinspeisungsgesetz’ of 1990, had almost no direct effect on PV in Germany. The FIT of 2000 has received much attention in the years after its introduction (e.g., Jacobsson and Lauber, 2006; Jacobsson et al., 2004; Lauber and Mez, 2004), but the significant changes in the FIT scheme for PV, especially since 2007, have not yet been comprehensively documented and studied in the academic literature.

4. Method

We employed qualitative case study research since this methodology allows us to obtain an in-depth understanding of the policy dynamics and the mechanisms driving them over time (Eisenhardt and Graebner, 2007; Yin, 2009).

For our analysis we drew on two main data sources. First, to obtain a broad understanding of the contextual factors we conducted a series of semi-structured interviews with 21 designated PV industry experts.⁵⁹ Experts were sampled in a way that ensured that they covered different positions in the industry and that they provided both insiders’ and outsiders’ perspectives on the policy-making process. Of the experts interviewed, 7 were directly involved in the legal process, e.g. by being members of the German national parliament, working in the ministry of environment or serving as experts for expert committees. Among those interviewees not directly participating in the political

⁵⁸ While we define PV as our unit of analysis, the fact that this technology is embedded in a larger technological system, encompassing for example the electricity grid, makes an isolated consideration of PV impossible. In our analysis, we therefore include developments in and effects on adjacent technologies whenever necessary.

⁵⁹ Interviews lasted between 60 and 90 minutes and were conducted by at least two researchers to ensure the reliability of the findings.

process were investors, project developers, representatives of firms producing PV modules and manufacturing equipment, scientists and market analysts.

Second, as the primary source of information, we conducted a comprehensive analysis of more than 700 archival documents describing both the process and outcome of policy-making for the German FIT system for PV. We began by collecting the legislative texts pertaining to the German Renewable Energy Sources Act (EEG) with its 8 amendments. These documents served as a data basis to describe how the policy as the *legislative basis* related to the German FIT has changed over time. To obtain an in-depth understanding of the *policy process* that led to the changes in legislation, we then searched the archive of the German National Parliament ('Bundestag') for documents containing the keywords 'solar', 'solar energy', 'solar power', 'sun power' and 'photovoltaic' (in German).⁶⁰ This search yielded 715 documents of which 170 were deleted because they were considered of little value for our analysis. Finally, to understand the *effects of the policy on the broader socio-technical system*, we gathered additional quantitative and qualitative data on annual and cumulative PV deployment, industry development, jobs, annual and cumulative costs as well as PV system prices in Germany. In this context, among other sources, we screened 6 additional expert studies dealing with the German FIT for PV as well as 166 issues of the leading industry magazine "Photon" from 1996 to 2011. An overview of the archival documents we analyzed as part of our study is given in Table 1. Moreover, Table A1 in the appendix contains a list of the 57 most important documents in chronological order.

⁶⁰To understand the origin of the 2000 Renewable Energy Sources Act, the analysis of archival documents comprised archival data reaching back as far as 1980.

Table 1: Overview of analyzed archival documents

Category	No. of Documents
Legislative texts pertaining to the German Renewable Energy Sources Act	8
Protocols of sessions of the German Bundestag	110
Legislative drafts and petitions	81
Protocols and reports of expert committees	104
Briefings by the German government (incl. EEG experience reports)	72
Protocols of parliamentary question times (incl. answers)	67
Minor interpellations directed to the German government (incl. answers)	88
Major interpellations directed to the German government (incl. answers)	23
Issues of industry magazine “Photon”	166
External expert studies	6
Sum	725

To derive theoretical insights from our data sources, the interview transcripts and archival documents were analyzed using qualitative content analysis. Following the logic of innovation system analyses, we first used ATLAS.ti to code the documents describing the policy process to identify prevalent issues, i.e. system failures and other drivers mentioned as a rationale for policy implementation in the policy discourse. Using a bottom-up, iterative coding procedure, we identified a total of 2,354 text elements which we grouped into 15 issue categories (see Table A2 in the appendix for an overview of the categories and their frequency of occurrence in the documents over time). In a second step, we then applied pattern matching to establish relationships between the identified issues, implemented policy measures and the observed changes in the socio-technical system (Yin, 2009). Triangulation of our various data sources allowed us to uncover for each point in time whether and why policy makers were acting upon prevalent issues in the socio-technical system, how the policy interventions taken resulted in changes in the socio-technical system and how these system changes, in turn, affected the issues discussed in the further political discourse. Taken together, this analysis provided insights on the relevance of system complexity, i.e., the extent to which developments in the system and consequences of policy interventions were intended or foreseen. By analyzing the rhetoric and action of the political actors in detail we could further control for the role of politics.

Table 2: Evolution of the German FIT System for PV from 2000 to beginning of 2012

Phase	Prevalent Issues in Socio-Technical System	Time of Policy Change	Parties in Gov.	Changes in Policy Design	Effect on Socio-Technical System
1	Lack of maturity and high cost of PV technology Lack of mass market for PV Insufficient financial incentive for power producers of PV Market power of large utilities Market support as chance to build PV industry and create jobs	2000	SPD & Green	Introduction of Renewable Energy Sources Act	First boost in deployment (cumulative capacity of 186 MW installed in 2001) No. of jobs grows slowly to 4000 in 2001 Rise in annual PV difference costs ⁶¹ from 19 M EUR in 2000 to 37 M EUR in 2001
				Technology-specific but size-independent remuneration of 51 EUR cents/kWh over 20 years Maximum size of 5MW for building integrated plants, 100kW for others Fixed degression of 5% p.a. Ceiling for cumulative installed capacity at 350 MW Exclusion of utilities with share of EEG electricity > 50% in overall sales from having to pay EEG apportionment ('Grünstrom-privileg')	
2	Market support as chance to build PV industry and create jobs Market support as chance to increase exports High cost and rising electricity prices (problematic especially for energy-intensive industry)	2002	SPD & Green	Ceiling for cumulative installed capacity raised to 1000 MW	Strong rise in deployment (cumulative capacity of 4,170 MW installed at the end of 2007) Reduction of PV system price from 6 EUR/Wp in 2002 to 4.3 EUR/Wp in 2008 Strong rise in no. of jobs to 40,400 in 2007 Rise in annual PV difference costs to 1.47 bn. EUR in 2007
		2003	SPD & Green	Reduction of EEG apportionment (0.05 EUR cents/kWh) for large electricity consumers facing international competition with a consumption > 100 GWh, electricity cost per gross value added > 20% Removal of ceiling for cumulative installed capacity and plant size Increase in remuneration for roof-top PV to 54.7 EUR cents/kWh	
		2004	SPD & Green	Changes in redistribution mechanism of EEG apportionment Adjustment of criteria for reduction of EEG apportionment for large electricity consumers to consumption > 10 GWh, electricity cost per gross value added >15%	

⁶¹ Difference costs are calculated as the difference between the total annual expenses for supporting renewables (FIT remuneration, balance energy) and the revenue from selling renewable electricity at the wholesale market. Dividing the difference cost by the volume of electricity produced under the FIT scheme yields the EEG apportionment.

Table 2 (ctd.): Evolution of the German FIT System for PV from 2000 to beginning of 2012

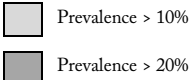
Phase	Prevalent Issues in Socio-Technical System	Time of Policy Change	Parties in Gov.	Changes in Policy Design	Effect on Socio-Technical System
3	High cost for society and rising electricity prices Excess remuneration and windfall profits for PV industry Increasing competition from China Risk of hurting domestic industry	2009	CDU & SPD	Dynamic degression of remuneration depending on deployment (basic degression of 8 to 10% for 2010 ± 1 percentage point if annual installed capacity < 1000 MW or > 1500 MW) ⁶² Requirement to install remote control and power measurement unit for plants > 100 kW Option of self-consumption (25.01 EUR cents/kWh) or direct marketing to third parties ⁶³	Further increase in deployment (cumulative capacity of 24,678 MW installed at the end of 2011)
		2010	CDU & FDP	Basic degression for 2010 changed to between 8% to 13% depending on system size Dynamic degression rate for 2011 raised (basic degression of 9% ± up to 4 percentage points depending on deployment in 2010) Additional one-time reductions of remuneration by 10% (July) and 3% (October) Reform of distribution mechanism underlying EEG apportionment	Slowing market growth Rise in no. of jobs to 150,000 in 2011 Rise in annual PV difference costs to 6.8 bn. EUR in 2011 Strong reduction of PV system prices from 4.3 EUR/Wp in 2008 to 2.05 EUR/Wp at the end of 2011
		2011	CDU & FDP	Adjustment of degression for 2011 by 3%, 6%, 9%, 12% or 15% depending on deployment in March to May 2011(target corridor of 2.5 to 2.5 GW newly installed capacity per year) Adjustment of degression for 2012 (9% basic degr., reduction or increase dep. on deployment in 2011)	
4	Increased power intermittency and power regulation Risk of reduced grid stability Lack of market integration High cost for society and rising electricity prices	2012	CDU & FDP	Alternative between limiting inverter power to 70% of PV plant capacity or installation of remote control for plants < 30 kW Remuneration for self-consumption depending on system size (max. 12.36 EUR cents /kWh) Further extension of reduction in EEG apportionment for large electricity consumers: criteria adjusted to consumption n > 1 GWh, electricity cost per gross value added >14% Limitation of 'Grünstromprivileg' (see Phase 1) to 2 EUR cents/kWh Introduction of market premium as incentive for direct marketing	?

⁶² According to the law, the target corridor for the dynamic degression should change over time. E.g., in 2011 the FIT should be adjusted up- or downward if in the previous 12 months the annual installed capacity was < 1200 MW or > 1900 MW.

⁶³ The option of self-consumption, despite being in the law, was not applicable at first due to the lack of an implementing decree.

Table 3: Relative prevalence of issues in phases

Issue Category	Relative prevalence of issue in phase			
	Phase 1: < 2000	Phase 2: 2000-2003	Phase 3: 2004-2010	Phase 4: 2011
Lack of maturity and high cost of PV technology	14%	3%	2%	1%
Lack of mass market for solar PV	11%	0%	0%	0%
Insufficient financial incentive for power producers of PV	26%	3%	0%	0%
Market power of large utilities	10%	3%	2%	0%
Market support as chance to build PV industry and create jobs	30%	38%	17%	3%
Market support as chance to increase exports	3%	13%	7%	1%
High cost for energy-intensive industry	0%	7%	4%	5%
High cost for society and rising electricity prices	3%	18%	18%	16%
Increasing competition from China	0%	0%	5%	1%
Excess remuneration and windfall profits for PV industry	0%	0%	11%	7%
Risk of losing public acceptance for policy and technology	0%	0%	2%	2%
Risk of hurting domestic PV industry	0%	0%	16%	4%
Increased power intermittency and power regulation	3%	7%	5%	17%
Risk of reduced grid stability	0%	7%	9%	22%
Lack of market integration	0%	0%	3%	21%



 Prevalence > 10%

 Prevalence > 20%

5. Evolution of the German FIT System for PV

In the following, we describe the evolution of the German FIT system for PV from 2000 to the beginning of 2012. For the sake of readability, we cluster the development of the instrument into four phases during each of which policy makers focused on specific changes in policy design. For each of the phases we first describe the main issues in the socio-technical system. We then discuss the implemented policy changes targeting these issues as well as the effects these had on the socio-technical system. During our description, we use the codes D1 to D54 to reference the original policy documents listed in Table A1 in the appendix. An overview of the four phases, displaying the respective system issues, implemented policy changes and effects on the socio-technical system is given in Table 2. Supporting the information in Table 2, Table 3 shows how the relative importance of issues in each of the phases has evolved over time.

5.1. Phase 1: Establishing a Sufficient Financial Incentive (until 2000)

Prior to the year 2000, development and deployment of PV technologies in Germany were not driven by national feed-in tariffs but a mix of direct R&D funding, smaller local initiatives and two large demonstration programs, the 1,000 and the 100,000 roofs program. In the year 1991, based on a report of a cross-party working group (the so-called 'Enquete Kommission' – see document D1 in Table A1 in the appendix), the first Feed-in Law ('Stromeinspeisungsgesetz'- D2) was established by the governing coalition consisting of the Christian Democratic (CDU) and the Liberal Democratic Party (FDP). The law was passed with strong parliamentary support in 1990 after the CDU/FDP leadership in the Bundestag had initially stopped a member's bill to create a market for renewable energies in 1989. However, this law "had no measurable effect on the use of photovoltaic power" (D7) since the remuneration at a level of 90% of the average customer purchasing price was much too low to cover costs of PV power producers.

Throughout its reign, the CDU/FDP government opposed any increase in the FIT for PV with the argument that subsidizing the technology was uneconomic and further market interventions should be avoided (D3, D5). Instead it was stressed that due to the early stage of development, support for R&D and demonstration was best suited to advance PV (D10). Politicians of the Social Democratic Party (SPD) and Greens, on the contrary, emphasized the importance of a mass market for lowering the costs of PV (D8). They pointed to the fact that other countries, such as Japan and the US, had already established more comprehensive market support schemes, raising concerns that Germany might lose the international race for PV industry development (D4, D6, D9, D10). Moreover, especially the Green party considered the broader market support of PV a means to break the market power of the large German utilities (D8).

When in 1998 the CDU/FDP government was replaced by a coalition consisting of the SPD and the Green Party, the new government set up a completely new feed-in law, the Renewable Energy Sources Act ('Erneuerbare Energien Gesetz' – EEG – D11).⁶⁴ The law consisted of 12 articles and was adopted on the 1st of April 2000. Similar to the first Feed-in Law, the EEG granted independent

⁶⁴The Minister of Economic Affairs, Werner Müller, opposed the idea of a FIT scheme and favored green electricity standards as a voluntary option or a quota system. The parliamentary groups of the Greens and the SPD outmaneuvered him by devising and passing their own law.

producers of PV access to the electricity grid if a grid connection was “necessary and economically feasible”. Beyond this, however, for the first time the law included a PV-specific remuneration of 51 EUR cents/kWh⁶⁵ at which grid operators had to purchase the generated electricity over a guaranteed period of 20 years. The remuneration paid by the grid operator was forwarded to the electricity utility which apportioned the extra costs (so-called ‘EEG apportionment’) to the electricity price of the end consumer. Only utilities whose total sales included more than 50% of FIT-eligible electricity were excluded from having to collect the EEG apportionment, creating an extra incentive for utilities to increase their share of renewables in their electricity portfolio. To account for the expected decreases in the cost of PV resulting from technological learning and economies of scale, the law included an annual degression of 5% in the FIT for newly installed plants as of 2002.⁶⁶

In combination with low-interest loans provided under the 100,000 roofs program, the significant increase in the remuneration for PV led to a surge in the market for PV technologies. Annual installed capacity escalated from only 9 MW in 1999 to more than its 15-fold in 2003 (see Figure 1). The first experience report on the EEG, commissioned by the German Bundestag and published in June 2002, noted that PV showed the smallest contribution to the electricity generation (0.05% in 2001) but the highest growth rates (D12). The EEG was subtly rated a success and it was expected that the additional incentives set by the 100,000 roofs program could be abandoned in 2004.

5.2. Phase 2: Removing Barriers to Market Growth (2000-2004)

With the EEG providing a sufficient financial incentive for an increased investment in PV, two issues emerged that the 2000 version of the EEG did not take into account. First, to allay concerns among opposition parties and consumer associations that the EEG would lead to steep increases in electricity prices, the EEG 2000 included a cap of 350 MW for the maximum cumulative installed capacity to be covered by the feed-in tariff. Simultaneously, the plants eligible for the remuneration were limited to a maximum size of 5 MW for roof-mounted PV and 100 kW_p for other facilities. In the view of an emerging domestic PV industry, both of these factors were considered potentially harmful barriers to

⁶⁵ All monetary values in this document are expressed in nominal terms.

⁶⁶ It is important to note that the degression mechanism leaves the tariffs of installed plants unchanged, i.e. plant operators are guaranteed the FIT tariff at the time of installation throughout the twenty years, irrespective of later changes in legislation.

the opportunity of establishing a leading market position and exporting domestic PV technology (D12). Second, with increasing deployment the share of the EEG apportionment in the end consumer electricity price rose from 0.2 EUR cents/kWh in 2000 to 0.4 EUR cents/kWh in 2004 which led to concerns about potential competitive disadvantages for energy-intensive sectors (D14, D16).

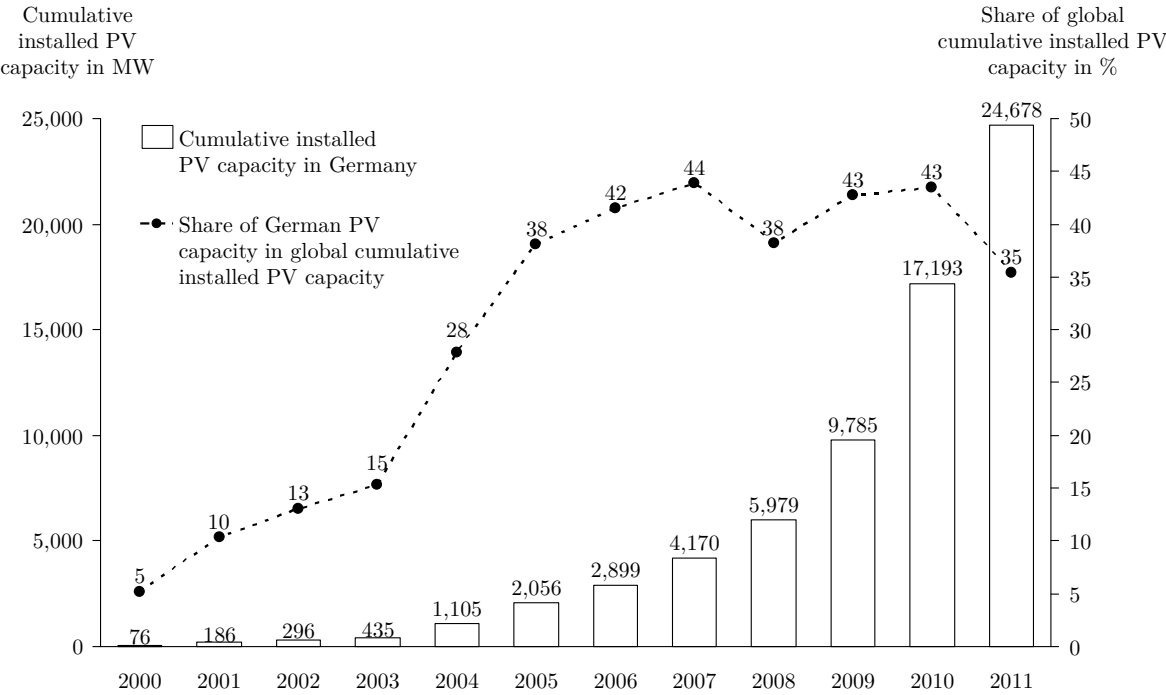


Figure 1: Cumulative installed PV capacity in Germany (data from BMU, 2012; EPIA, 2012).

To address these issues, in 2002 the German Bundestag adopted an addition to the EEG which raised the ceiling to 1000 MW (D13). Moreover, in a first amendment of the EEG in July 2003, an article was added that limited EEG apportionment for large electricity consumers that a) faced international competition and b) had an electricity consumption of more than 100 GWh and a share of electricity costs in gross value added of more than 20% to 0.05 EUR cents/kWh (D15).⁶⁷ In a second amendment in December 2003 (D18), the ceiling and the limit to eligible plant sizes were completely removed. For roof-mounted PV the remuneration was raised to up to 57.4 EUR cents/kWh which was justified by the fact that with the end of the 100.000 roofs program private households could no longer apply for complementary low-interest loans (D19). All of these changes were mainly promoted by the SPD/Green government coalition. Yet, the EEG also enjoyed support by many politicians in the CDU who, while pointing to areas of improvement, praised its general effectiveness (D14, D17).

⁶⁷ The exceptions for large electricity consumers were also supported by the opposition party CDU.

In July 2004 the EEG 2000 with its additions and amendments was substituted by a completely overhauled new EEG, consisting of 21 articles (D20). The revision had officially been stipulated in the EEG of 2000 and reinforced the development reflected in the previous additions. Several articles were added that detailed the processes of remuneration payment and grid connection to ensure a higher investment security of independent power producers. Furthermore, the limitation of the EEG apportionment for large electricity consumers was extended to include all companies that used more than 10 GWh of electricity and had a share of electricity costs in gross value added of more than 15%. Similar to the 2003 amendments, the EEG 2004 was championed by the SPD/Green government. The CDU would have supported the legislation if it had been set to run out by 2007.

The increase in the remuneration for rooftop PV and the removal of the ceilings for maximum plant size led to a fundamental boom of installations in Germany. The installed capacity rose from 435 MW at the end of 2003 to almost 6 GW at the end of 2008. The 2007 experience report noted that the 2010 target for deployment of PV would already be reached at the end of 2007 (D27). Due to its positive effects on domestic job creation, CO₂-free electricity supply and innovation, the overall assessment of the law was very positive. Especially the growing number of jobs in firms producing and installing PV modules and manufacturing equipment (see Figure 2) led to an unprecedented excitement among politicians of all parties. In many debates, the EEG was praised as a success story (D22, D23, D26, D28, D29, D30). Even the FDP, which as the only party favored “market-based instruments”, such as tradable green certificates over a FIT, urged measures to support the export of German PV technology (D24, D25).

5.3. Phase 3: Limiting Rising Costs for Society (2004-2011)

Prior to 2006 the SPD and the Green Party, as the originators of the EEG, had been able to justify the public costs for PV by pointing to the positive economic, ecological and social side effects of the FIT which were supposed to outweigh the investments in the medium term. Furthermore, politicians of both parties pointed to the large amounts of public spending that had been directed to other energy technologies, e.g. nuclear power, in the past (D17). In contrast to this, some members of parliament of the CDU and FDP voiced criticism regarding the high social costs resulting from the FIT for PV, e.g. in a large interpellation in 2004 (D21). However, all parties generally shared the goal of supporting PV and especially after a government consisting of SPD and CDU had been elected in 2005, critics of the EEG in the CDU maintained a low profile.

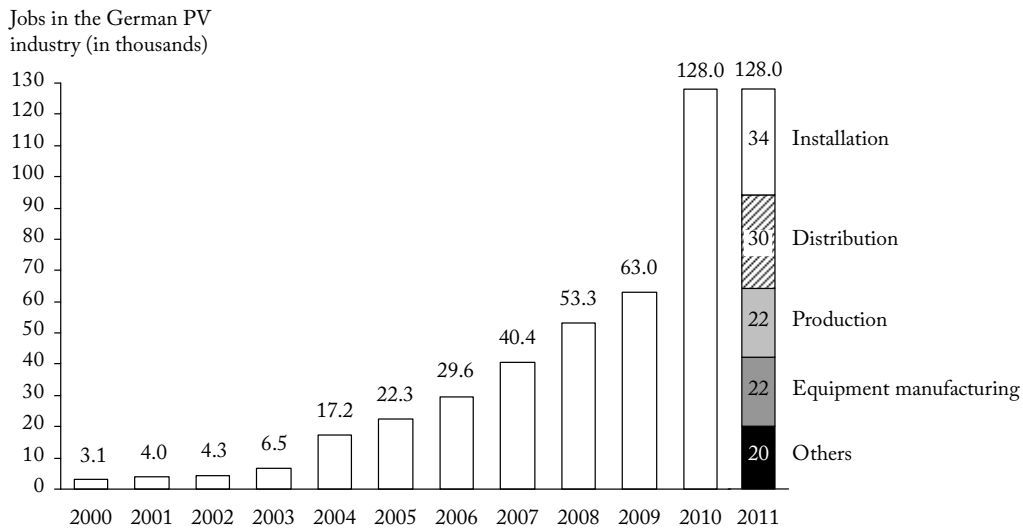


Figure 2: Development of jobs in the German PV industry (data from BSW Solar, 2012).

With the steep increase in deployment that occurred from 2004 to 2008, the costs that had to be borne by the electricity consumer became increasingly significant and the focal point of the political debate. In 2008, the extra cost for electricity consumers due to PV support through the FIT amounted to almost 2 bn EUR – an increase of more than 600 percent compared to the level of 2004 (see Figure 3). In addition, it showed that production costs for PV modules during the years 2004 to 2008 had decreased at a much faster rate than the remuneration paid through the FIT system (D34). These cost reductions, which were the result of successful innovation efforts of firms and economies of scale, led to considerable windfall profits for technology and power producers (D31, D34).

In response to these challenges, in 2009 a new EEG was enforced which contained specific measures to “dampen the market development”, limit additional costs for consumers and reduce windfall profits (D33). As the most significant change, the static degression of 5% was substituted by a dynamic degression (‘flexible ceiling’) which meant that the level of remuneration paid for new plants was dependent on the installed capacity of PV in the previous year. This new mechanism, which had been suggested by the Green Party to avoid a fixed ceiling, was supported by all parties except the LINKE (D32). As a measure to reduce adverse effects of PV on grid stability and avoid investments in distribution grids, the 2009 amendment of the EEG also introduced targeted incentives for self-consumption of electricity. Furthermore, based on recommendations in the 2007 experience report, the amendment to the EEG in 2009 contained a new article which required plants with a size larger than 100 kW to implement a remote control and power measurement unit. This measure was meant to provide grid operators with the possibility to disconnect larger plants from the grid in case of instability. To make up for the financial losses occurring during such a period of transitional grid

enforcement, plant operators were legally guaranteed compensation at the level of lost income. The EEG 2009 also reformed the redistribution mechanism underlying the EEG apportionment. Instead of purchasing the electricity and bundling it into contracts to be sold to electric utilities, grid operators were now required to directly market the electricity bought from PV plant operators at the electricity spot market. Moreover, to slowly integrate the renewables into the market and reduce mismatches between electricity demand and the supply, the EEG 2009 also introduced the option for plant operators to forgo the FIT and directly market their electricity to third parties.

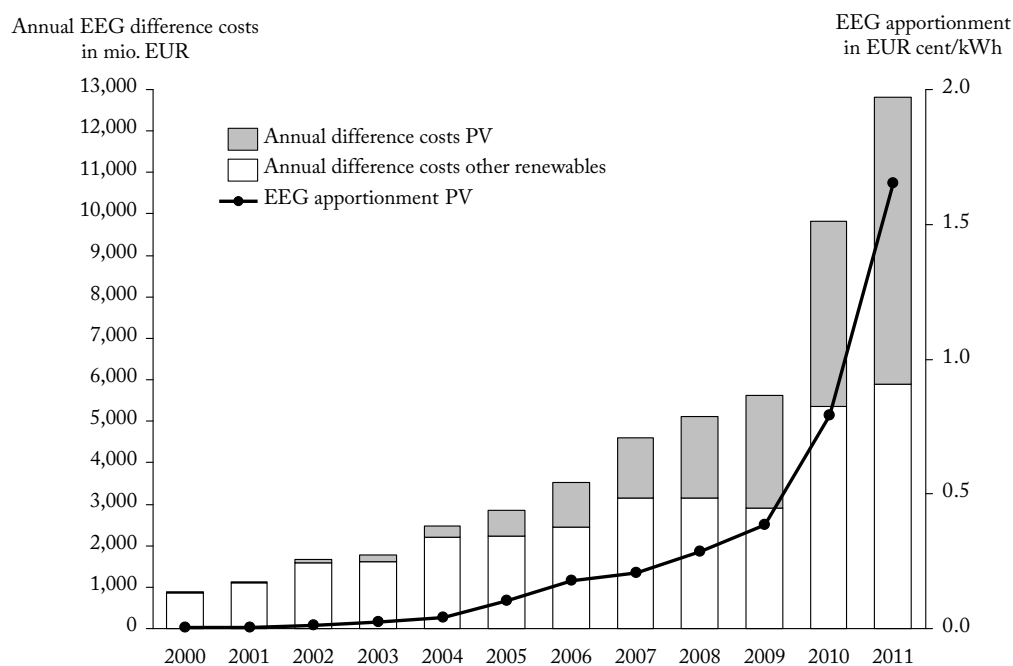


Figure 3: Development of annual EEG difference cost and apportionment for solar PV in Germany (data from BDEW, 2011).⁶⁸

Despite the (moderately) increased depression of FIT levels, deployment of PV kept rising at strong rates. Due to overcapacities among producers of PV modules, an increasing supply of low-cost modules from Asia (especially China) and a significant drop in prices for the raw material silicon (D38, D39, D40), PV system prices plummeted by 29 percent from 4,225 EUR per kW_p at the end of 2008

⁶⁸ It should be noted that with the EEG 2009 the cost redistribution mechanism of the EEG was changed in a way that renewable electricity was directly marketed on the wholesale market. The increased supply of renewable electricity led to a reduction in wholesale electricity prices (so-called ‘merit order effect’). Since the wholesale price serves as a benchmark for calculating the difference cost, falling wholesale prices contributed to a rise in annual difference costs.

to 3,000 EUR per kW_p at the end of 2009 (see Figure 4). Since the FIT level declined at a much lower pace, profits of both producers and investors rose. Together with the breakdown of the Spanish PV market, which now could no longer absorb the large quantities of PV modules produced (D38), this led to a record capacity of 3.8 GW being installed in Germany in 2009. The fact that this further raised the annual difference costs to be carried by consumers was deemed particularly undesirable since the market share of German manufacturers in global PV cell production had fallen quite significantly since 2007 and more and more modules installed in Germany were supplied by Chinese manufacturers (see Figure 5). Supporters of the EEG pointed to the fact that, despite the rising market share from Chinese suppliers, Germany maintained a stronger position in the fields of inverters, manufacturing equipment and poly-silicon production (see Figure 6). Nevertheless, a number of media reports appeared that saw the FIT itself as one of the main reasons for the competitive disadvantage of the German PV industry which, in the face of generous support had neglected technological innovation and geographic diversification (D35, D43). Formerly quoted as exemplary, the support for PV was now criticized even by advocates of the German FIT system who worried that the developments within PV could reduce the public acceptance of renewables and undermine the legitimacy of the FIT system as a whole (D37, D47, D48, D49, D51, D52).

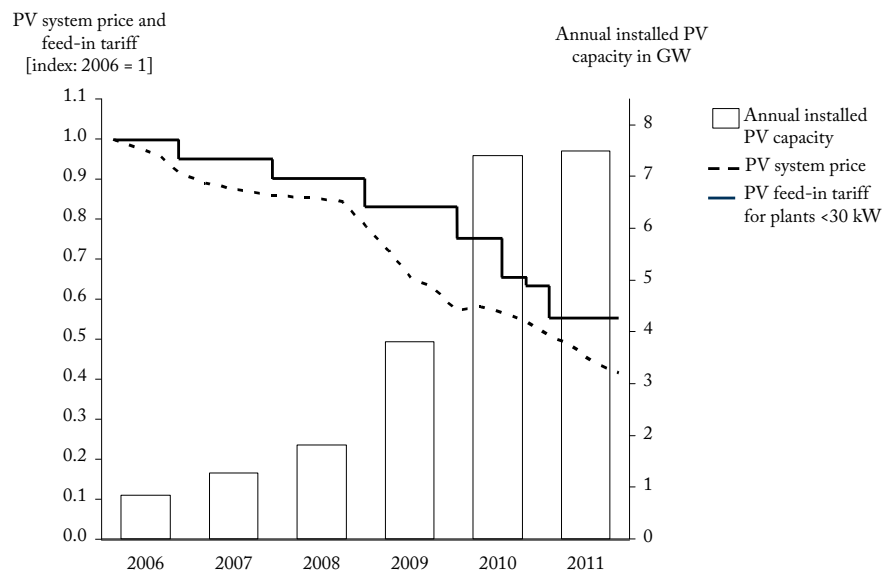


Figure 4: Development of feed-in tariff, PV system price and annual installed capacity of PV in Germany (data from BMU, 2011; BSW Solar, 2012; EPIA, 2012).

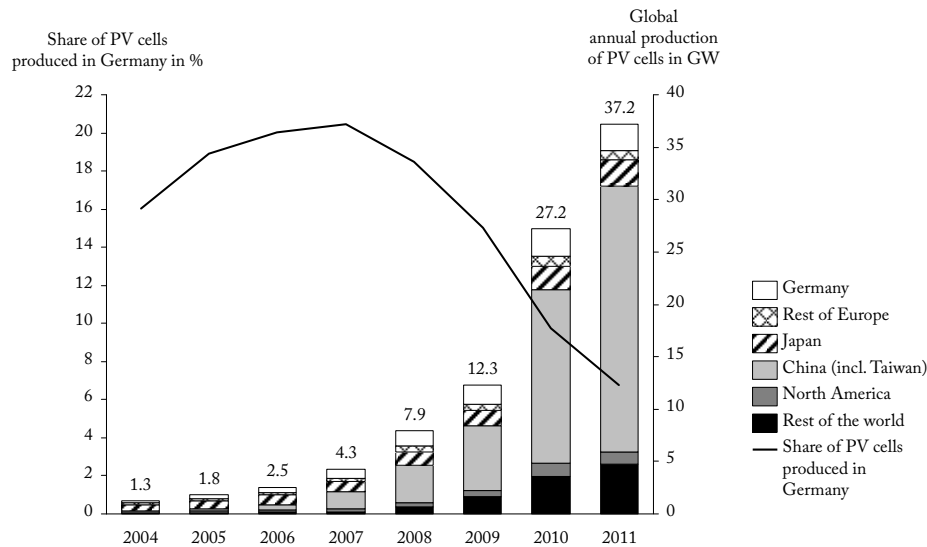


Figure 5: Global PV cell production and share of PV cells produced in Germany (data from Photon, 2012).

In reaction to these developments, the conservative government consisting of CDU and FDP, which had replaced the CDU/SPD government in September 2009, introduced a legislative draft according to which FIT levels of PV ought to be cut by 20 percent (D36).⁶⁹ Although, particularly in the later phases of the legislative process, there was a general consensus among all parties that the level of the FIT for PV had to be reduced, SPD, Greens and LINKE opposed such drastic reductions, pointing out that they would hurt the domestic industry and that windfall profits in the PV industry were negligible compared to the profits made by the large utilities (D35, D41, D42). Finally, in August 2010, an amendment of the EEG was enforced that significantly reduced remuneration for all system sizes retroactively for July 2010 (D46). Degression for 2010 and 2011 was adjusted upward. Furthermore, two one-time reductions were applied which lowered remunerations by 10% and 3% in July and October 2010 respectively. The fact that reductions were much lower than originally envisioned was mainly due to the fact that conservative representatives from eastern states, in which the majority of PV cell and module producers are located, opposed any one-time reductions in the FIT beyond 10% (D44).

⁶⁹ The fact that, despite previous opposition by the FDP, the FIT was not abandoned by the conservative-liberal government can be attributed to the fact that solar power enjoyed widespread support in the German population and that with 60,000 jobs the industry had become an important economic factor. Interestingly, even within the FDP the EEG was supported by the majority of the members. For example, in May 2009 a motion that endorsed the EEG and was binding for the FDP leadership was accepted by the floor of the party convention.

Global market share
in PV products in 2011

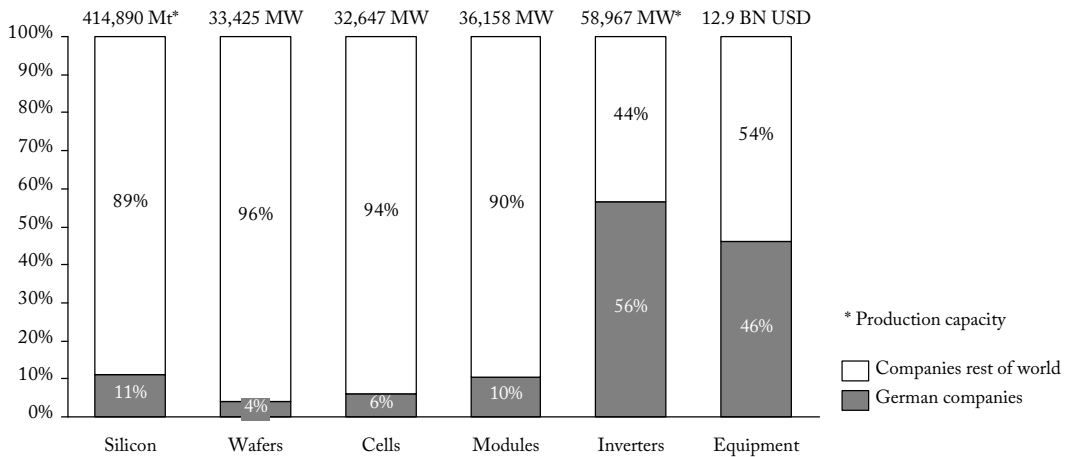


Figure 6: Global market share of German firms in PV products in 2011 (data from GTM Research, VDMA, NPD Solarbuzz).

Despite these measures, annual installed capacity in 2010 reached an all-time high of more than 7.4 GW. Therefore, depression rates were further raised in another amendment of the EEG in May 2011 (D53), such that the FIT levels at the beginning of 2012 reached a level of only 40% of those in 2004. Opposition to these cuts in the FIT was limited (D50, D51). In 2011 another record capacity of 7.5 GW was installed that considerably exceeded the target corridor of 2.5 to 3.5 GW annually. With annual difference costs amounting to more than 6.8 bn EUR in 2011, costs remained an important topic in the public and political debate preceding the adoption of the EEG 2012.⁷⁰

5.4. Phase 4: Ensuring Seamless Integration into the Market and the Electricity

Grid (since 2011)

With the EEG 2012 the CDU/FDP government further extended the reductions in the EEG apportionment for energy-intensive companies, officially to alleviate potential negative consequences from rising electricity prices.⁷¹ Since this implied an additional rise in the EEG apportionment for

⁷⁰ That the German FIT for PV remains politically debated is also due to the fact that the ongoing growth of distributed generation poses a threat to the business models of the four large German electric utilities (see, e.g., Becker, 2011).

⁷¹ It is important to note that by the time that the reductions were further extended, a large proportion of the energy-intensive industries were already largely exempted from having to pay the EEG apportionment and

non-privileged consumers, Greens, SPD and LINKE accused the government of not being interested in lowering the burden for consumers (D56, D57). At the same time, however, with PV deployment strongly rising and prices of PV systems strongly declining, two important questions other than social costs moved higher up on the political agenda: 1) How to integrate the increasing capacity of intermittent power into the electricity grid without compromising its stability and 2) how to structure incentives in a way that allows seamlessly phasing out the FIT scheme once cost competitiveness is reached (D54).

After deployment continued to rise in 2009 and 2010, the issue of grid integration gained increasing prominence. While some experts did not see any immediate problems with regard to the grid (e.g., Christian von Hirschhausen, German Institute for Economic Affairs), others openly warned of “considerable conflicts” (Rainer Baake, German Environmental Aid, D45) and “massive problems” (Stephan Kohler, German Energy Agency, D54) with grid stability if no measures were taken. Hence, the question of grid integration was taken on more seriously in the political debate and addressed in the EEG 2012 (D57). The new legislation consisting of 88 articles became effective in 2012. Among others, it required new plants of any size to have a remote control, allowing the grid operator to disconnect it from the grid.⁷² Furthermore, the fixed remuneration for self-consumption was replaced by a self-consumption bonus paid in addition to substituted retail electricity prices. This measure was expected to foster household investments in energy storage and demand-side management (D54).

To incentivize market integration of PV, the EEG 2012 granted operators a market premium if they renounced the FIT and directly marketed their electricity on the spot market. While in general this step was considered useful by experts, they criticized the decision of the government to simultaneously limit the possibility for utilities to benefit from the ‘Gruenstromprivileg’ (see phase 1), which had previously been the most important scheme for incentivizing direct marketing (D54). Moreover, the direct marketing of PV is complicated by the fact that the change in the redistribution mechanism in

simultaneously benefited from lower wholesale electricity prices due to the merit order effect (see above). With the EEG 2012, the possibility of not having to pay the EEG apportionment was extended to smaller companies. Applications for exemptions were handled rather generously by the responsible Ministry of Economic Affairs, to a degree that induced the EU commission to start an investigation on illicit state aid (Nestle and Reuster, 2012)

⁷² Only for plants with a size smaller than 30 kW, could the operator alternatively choose to limit the power of the inverter to 70% of the plant capacity, thereby reducing the intermittency of PV electricity.

the EEG 2009 PV itself had strongly contributed to lowering peak-load electricity prices through the ‘merit order effect’ (D54, D55). Since in 2012 the costs of PV are still comparatively high, only a very small percentage of PV electricity is directly marketed. With LCOE having fallen below retail prices, however, direct marketing of PV is expected to play an increasing role in the future as the political support through the FIT can slowly be phased out (D54).

6. Discussion

Based on our analysis of the evolution of the German FIT system for PV, in the following we discuss how policy interventions both drove and were driven by technological change. Building upon this, we propose a theoretical model describing how the complex dynamics of socio-technical systems shape the process of policy interventions targeted at inducing technological change. Finally, we discuss how our study might contribute to an improved integration of the literature on innovation systems and policy learning.

6.1. The German FIT as an Example of Policy Learning

The description of our findings in section 5 shows that the German feed-in tariff system for PV went through a large number of legislative changes, each of which addressed specific issues in the socio-technical system. In part, these changes can be explained through characteristics of and factors residing in the political system. For example, the legislative changes in the exemptions implemented for energy-intensive industry have been strongly driven by party politics. Similarly, the decision to first implement, later raise and finally remove the ceiling to the maximum cumulative capacity of PV constitutes a typical case of learning among policy makers who initially were not sure about the cost effects that providing a feed-in remuneration for PV would have. In the case of the German feed-in tariff system for PV such changes were facilitated by the fact that, from the start, policy makers were aware that the law had to be revised. Consequently, they implemented a revision cycle that was supported by expert consultations, frequent political interpellations and numerous experience reports commissioned from external authorities. This institutionalization of learning on the side of the policy maker allowed a continuous evolution and adaptation of the legislation.

6.2. Policy-Induced Technological Change as a Driver of Policy Dynamics

While the German FIT for solar PV can therefore be regarded as a good example for how the formal institutionalization of learning mechanisms can support the policy process, our analysis revealed that factors residing in the political system are necessary but not sufficient to explain the evolution of the policy. Rather, we found that many of the changes in the German FIT for solar PV can be traced back to *technological change in the socio-technical system* that policy makers intervened in. While policy interventions often contributed to resolving the issues in focus, in many cases technological change *induced by the FIT scheme* led to the emergence of new, unexpected issues that policy makers addressed in subsequent steps. In the following we present three examples to illustrate this point.

A first example for how technological change influenced policy dynamics are the regulatory changes that policy makers implemented in response to the unexpectedly high rate of policy-induced PV deployment. Since about 2004 the speed of deployment strongly exceeded what policymakers had envisioned or even thought was technically feasible. This rapid diffusion was made possible, amongst others, by innovations in mounting and installation technology, by the emergence of a sophisticated supply chain that allowed new systems to be designed and installed within a matter of days, by innovations in business models and financing schemes, by innovations in remote control systems, inverters and other means of grid integration and not least by spreading knowledge and awareness. The underestimation of the speed of PV deployment led policy makers to significantly misjudge the social cost of the FIT scheme. The German Ministry of the Environment, for example, stated that “in case of the desired, strong growth of renewable energies the burden [for consumers] will amount to mere 0.1 EUR cents per kWh in a couple of years” (BMU, 2000). This quickly turned out to be grossly over-optimistic. By 2003, the EEG apportionment, then still mainly driven by the other renewables, increased to 1.5 cents per kWh. With the surge of PV it escalated to 3.53 cents per kWh, more than the 35-fold of the original estimate, in 2011. As a consequence of this rise in costs, policy makers implemented a number of changes to the FIT. As the overall expenditures for the FIT scheme depend on the amount of annual PV deployment, they conducted a series of reforms of the remuneration rates and the degression mechanism, aimed at slowing down annual installed capacity. Also, the more recent efforts to address issues of grid and market integration can be considered a direct result of high deployment rates. Already in the 1980s, well before FITs were put in place, it was known that deploying large amounts of PV as an intermittent energy source would put stress on the electricity grid (D1). Yet, the fact that the first versions of the EEG up to 2009 did not contain any

measures addressing this issue indicate that policy makers did not expect integration of PV capacity to become a problem in the near future. With installed capacity of PV continuously growing at an unpredicted pace, first measures were finally implemented in the EEG 2009 that were directly targeted at enhancing grid stability, such as remote control or the limitation of inverter power. Moreover, in 2012 a highly controversial program was put in place that required operators of PV plants to retrofit existing systems to avoid fluctuations in the power frequency (the so-called ‘50.2 Hertz problem’), clearly showing that the issue of grid integration had previously been undervalued by regulators.

A second example for how unexpected technological change affected the policy dynamics is the strong reduction in the PV system costs, enabled by the fast PV deployment. From the beginning the German FIT for PV was designed to foster technological innovation and lower the cost of the technology, e.g. by enabling mass production. In view of this, the first EEG already included an annual degression of 5%, which as a policy maker we interviewed reported, had been chosen based on “usual learning rates of comparable industries”.⁷³ However, “technology costs fell much faster than [had] been expected” which was due to “economies of scale and research activities by private corporations which have been sparked by the EEG” (Katharina Reiche, Parliamentary Secretary of the Ministry of the Environment, D34). The complex relationship between demand, production capacity investments, technological change and competition, lead to a very erratic cost curve over the last ten years, which required numerous changes to the policy to limit windfall profits for industry. The rapid cost decreases, in turn, contributed to an ever faster deployment of PV, thereby exacerbating existing problems.

⁷³ Although the degression of 5% turned out as too low for PV, it was much lower for the other technologies under the EEG.

Finally, a good example for how the diffusion of technological knowledge – another dimension of technological change – can affect policy dynamics is the rise of the Chinese PV industry. Until 2007, German manufacturers were considered “world market leaders” (D24) and politicians of all parties were enthusiastic about the creation of jobs in an emerging industry which had been an important in developing the FIT. However after 2004, shortages in the supply of wafers, cells, and modules due to the unexpected demand opened up a window of opportunity for Chinese cell and module producers, which were able to generate revenues by selling their products on the German market. The Chinese companies “invested these resources in research and development” (D41) and modern production equipment, which was often supplied by Western equipment manufacturers. By providing the demand and by enabling the corresponding knowledge spillovers, as a policy maker we interviewed admitted, the German EEG itself “played a decisive role in the emergence of the Chinese PV industry”.⁷⁴ With increasing shares of imported technology, at some point the EEG benefited foreign producers more than the domestic industry. This jeopardized the legitimacy of the entire support scheme and became an important topic in the political discussion on FIT reforms.

Summarizing the previous statements, Figure 7 provides an overview of the role that policy-induced technological change played in the evolution of the German FIT for PV. It is important to note that this figure *does not paint a holistic picture of all drivers of policy and technology evolution* in the case of the German FIT for PV but focuses on depicting the interactions between changes in policy and technology.⁷⁵ Despite its simplifying nature, the figure indicates that in many ways technological change induced by policy makers led to the emergence of new prevalent issues which, in turn, were addressed by policy makers in subsequent steps. While policy makers tried to anticipate technological developments when crafting legislations, we find that many developments in the technological sphere triggered by policy interventions came as a surprise or were underestimated with regard to timing or scale. As one of the experts we interviewed reported, it is hard for policy makers to proactively address issues since “every change in a detail [of the regulation] can develop a dynamic which you did not intend”. In line with this, one policy maker we interviewed expressed that “with the EEG we are

⁷⁴ It should be noted that the emergence of the Chinese PV industry was strongly driven by the decision of the Chinese national and provincial government to offer strategic support for the sector, e.g., by offering low-interest loans through the Chinese Development Bank (see, e.g., Grau et al., 2012).

⁷⁵ For example, in contrast to Figure 8 following on page 23, the figure does not consider the role of politics or foreign policies for the dynamics of policy and technologies.

getting to the limits of what policy can shape. It is difficult to foresee the development, which is why we constantly have to reconfigure the legislation”. When developing schemes for market support, policy makers therefore “have to react to the tempestuous technological developments in the market. Over and over, we will have to react.” (Dr. Norbert Röttgen, former German Minister for the Environment, D43). While in many other countries the challenge of reacting to unexpected issues might have induced policy makers to cancel (or not even start) the support scheme, in Germany the high public support for renewables and PV, the existence of a domestic industry with related jobs and the political will of keeping markets open to new entrants prevented such a development.

6.1. Framework ‘Compulsive Policy-Making’

In order to translate our findings into a more abstract representation we propose the theoretical framework depicted in Figure 8, that directly addresses our research question of how the complex dynamics of socio-technical systems shape the process of policy interventions targeted at inducing technological change. We suggest that at each point in time, political discussions revolve around a number of prevalent issues in the socio-technical system (1). When designing policy incentives (2), policy makers directly address these issues and also try to foresee future ones. In general, however, changes in policies are only directed to a small subset of particularly prevalent issues and rarely present accurate answers to less immediate, future issues. This can be explained by the fact that, in general, policy makers possess limited capacity and foresight (a). More importantly, however, policy interventions (c) themselves often lead to technological change (3) that may resolve the immediate bottleneck but, through complex system interdependencies (e), leads to the emergence of new issues (1). These issues in turn, are addressed by policy makers by changing the focus in policy design and adjusting existing policies (2). The time it takes for issues to be resolved varies considerably depending on the detailed nature of the issue. As a result, changes in policy design are usually directed to a number of novel issues while simultaneously addressing older, persisting ones.

While the majority of issues we found in the history of the German FIT for PV can be considered at least partly self-inflicted, there were also developments within the socio-technical system that were beyond the direct control of German policy makers, e.g. the collapse of the Spanish market in 2009 that raised installations in Germany (d). Furthermore, throughout the evolution of the German FIT system for PV changes in policy design were impacted by politics (b). In the early phases of the German FIT system for PV, developments were strongly driven by political interests and opportunities, such as reducing the market power of large utilities and supporting a domestic PV industry. In the

further evolution of the German FIT system for PV, however, unforeseen issues emerged that exerted direct pressure on policy makers to change the policy design. Political debates became more technical with policy makers increasingly *reacting to* rather than *proactively shaping technological change*. Despite remaining considerable discrepancies between the political parties regarding the appropriate means, a broader consensus can be observed that particular issues (e.g. rising social costs or looming grid instabilities) needed to be tackled.

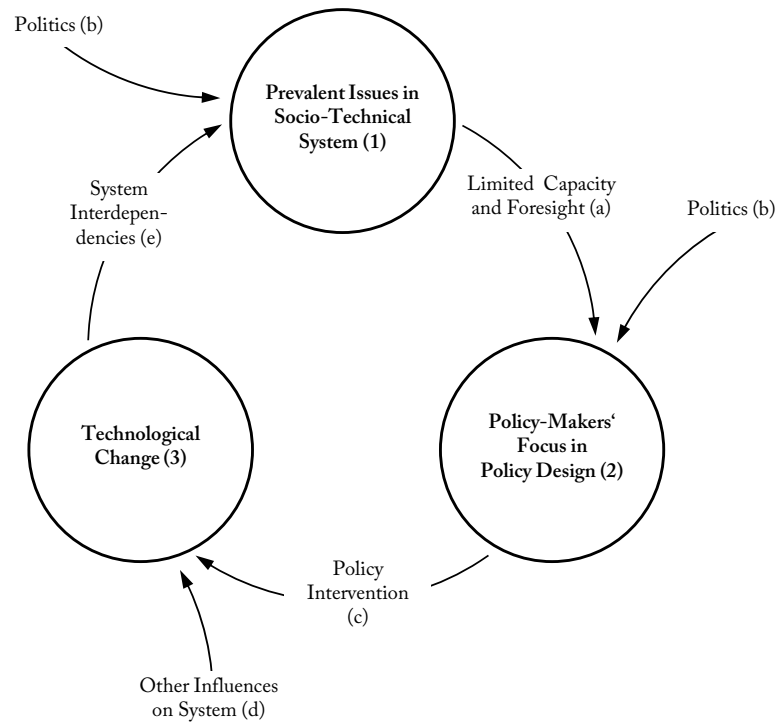


Figure 8: Framework ‘Compulsive Policy-Making’.

We argue that the cycle of issues and solutions we describe in Figure 8 shows strong similarities with what Rosenberg (1969) labeled ‘compulsive sequences’. Studying the evolution of technical systems in the machine tool industry, Rosenberg finds that at any given time firms in the industry focused their search processes on a small number of clearly identifiable problems which constitute the bottleneck of the technical system. Eventually, this search then led to a change in the system which resolved the bottleneck. However due to interdependencies between the system elements, the resolution of the bottleneck caused new bottlenecks in the system to emerge. Since these needed to be resolved to further increase the performance of the technical system, the firm’s direction of technical search

shifted to the new bottleneck, leading to a continuous cycle of problems and solutions that shapes the evolution of technical systems.⁷⁶

While obviously there are a number of important differences between a firm trying to improve a technology and policy makers intervening in a socio-technical system (e.g. in terms of the number of actors involved and the decision making process), we maintain that the general pattern is surprisingly similar. Building upon Rosenberg's terminology, we therefore label the process shown in Figure 8 'compulsive policy-making'.⁷⁷ It is important to note that in this context, 'compulsive' does not imply a lack of agency of policy makers in the political process. Rather, it describes the general phenomenon that interventions in socio-technical systems targeted at inducing technological change alter the configuration of the system, thereby causing changes in the prevalent issues and exerting a pressure on policy makers to change the focus in policy design.

The difference between the presented framework and existing frameworks of policy learning – such as Lindblom's (1959) 'science of muddling through' – is that 'compulsive policy-making' focuses on the influence of technological change on the dynamics of policy-making. The literature on policy learning primarily explains the iterative nature of the policy process based on *factors residing in the political system*. For example, Lindblom stresses the limited capacity of public administrators in dealing with complex problems as the main cause for policy iterations. Policy makers cannot go through the process of identifying all possible goals and values, listing all possible policy measures and choosing the best one. Therefore, according to the framework of 'muddling through', they pick a solution that best suits their immediate needs and are forced to make subsequent changes to the policy to correct for earlier mistakes. The concept of 'compulsive policy-making' also tries to explain the iterative nature of the policy processes. However, complementing existing concepts in the literature on policy learning, it focuses on *factors residing in the socio-technical system that policy makers attempt to change* as an

⁷⁶ Rosenberg's concept of 'compulsive sequences' was later taken on by Hughes' (1983) in his work on large technical systems. Similar to Rosenberg, Hughes suggests that complex systems evolve in an uneven manner since at each point in time there are particular system components – so-called 'reverse salients' – that lag behind other system components (e.g. in terms of efficiency). Since these reverse salients are interconnected with the other system components, their presence retards the overall performance of the technical system. Therefore, Hughes suggests that at each point in time innovative activity will concentrate on 'correcting' the reverse salient.

⁷⁷ In fact, in a footnote of his original article Rosenberg (1969, p.23) himself points to parallels between his framework and the political process.

explanation for policy dynamics. We argue that even if policy makers have the capacity and knowledge to design a policy that resolves a prevalent issue in the short-term, endogenous technological change induced by the policy measures can lead to a situation where unforeseen issues emerge that need to be addressed by policy makers in the future. In this sense, our framework points to an important driver of policy change other than policy failures, changes in political majorities or exogenous changes in the wider socio-economic environment (e.g., demographics or the world economy). Moreover, by drawing on the concepts of system issues and interdependencies, our framework describes concrete mechanisms rooted in the socio-technical system that affect the direction of policy-making.

In general, we would expect compulsive policy-making to be present in most policy fields as most policies will induce some technological change if the latter term is just defined broadly enough. Hence, policy-induced technological change operates in parallel with other dynamics driving policy learning. Still, we propose three criteria that define the conditions under which compulsive policy-making is likely to play a particularly important role: 1) The policy under consideration has a strong innovation policy component, such that it triggers technological change (see arrow ‘c’ in the framework), 2) policy plays an important role in driving technological change in the socio-technical system compared to other influences, such that technological change is largely endogenous (arrow ‘d’) and 3) the elements in the socio-technical system are interdependent, such that the outcome of policy interventions has systemic implications and is hard to foresee (arrow ‘e’). For example, implementing a change in income tax is not likely to induce strong dynamics of compulsive policy-making, simply because the direct effects of this policy change on technological change are probably limited. On the contrary, we would expect compulsive policy-making to be more prevalent in the case of stem cell research as all previously-mentioned criteria are fulfilled to a larger extent.

Overall, a main benefit of our framework lies in providing an additional lens on the drivers of and need for policy change, particularly in the context of innovation policies, as it draws attention to mechanisms that have not previously been stressed in the literature on policy learning. We suggest that a critical task in designing effective policies targeted at fostering technological change lies not only in developing adequate governance mechanisms based on existing knowledge but in *investing resources into better understanding the dynamics of the system to be intervened in*. Our study stresses the potential that lies in developing a profound knowledge about processes related to technological change and leveraging this knowledge when designing corresponding policies. For example, while according to learning curve theory, cost reduction in solar PV technology is a function of deployment, German policy makers chose a degression mechanism that reduced the remuneration for newly installed plants

as a function of time. A more profound understanding of the dynamics underlying cost reductions at the time of policy development might have prevented many of the iterations we have seen. Due to the complex nature of socio-technical systems it does not seem generally possible to accurately foresee the outcome of policy interventions based solely on the analysis of historical cases. Therefore, we suggest making system analysis an integral part of policy monitoring. Rather than only tracking the outcome of policy interventions, policy makers should try to understand the root cause of unexpected technology dynamics and their relation to policy. In this context, it seems important to develop close ties to industry and research institutions to develop a profound knowledge of the drivers of technology developments, which can then be leveraged to continuously improve regulations.

A profound understanding of system dynamics is also *important for policy makers who wish to adopt policy instruments that are already successfully used in other countries*. Our study shows that the effectiveness and appropriateness of policy instruments at any given time is at least partly conditional on previous policy interventions and resulting changes in the socio-technical system. This implies that, although policy makers should leverage the lessons learned in other countries, there is a limit to which policy features implemented in other countries can be successfully copied. For example, the diffusion of solar PV in the German socio-technical system may now have built up enough momentum, e.g., in the form of trust in the system and vested interests, that the system can wither policy interventions aimed at increasing the cost effectiveness or grid friendliness of the policy support. Introducing measures such as the mandatory direct marketing of renewable power in a nascent system without the same history of PV deployment may not show the same positive effects as in the German context as they may induce investment uncertainty and derail the diffusion of the technology before it has even picked up momentum.

6.2. Innovation Systems and Policy Learning: Towards an Integrated Framework

By stressing the role of policy learning and adaptation in the context of innovation systems, our framework represents a first step towards a closer integration of the literature on innovation systems with the work on policy learning. Up to this point, there has been little academic work connecting these two streams of literature. Our empirical analysis of the German FIT system for PV suggests that this current divide is unfortunate as the approaches hold a lot of potential for informing each other. The innovation systems approach represents a powerful heuristic for identifying system failures (or issues) but tends to underestimate the effect of politics and limited foresight. In contrast, the literature on policy learning puts strong emphasis on the inherently political, unpredictable and emergent nature

of policy-making. As the rather effective German FIT for solar PV shows, however, this potentially undervalues policy makers' capacity to purposefully alter socio-technical systems. To reconcile these two perspectives, it seems that we require a better understanding of the detailed mechanisms which shape the dynamics of policy interventions in complex socio-technical systems. Our framework builds upon the idea of system failures or issues as the focusing devices of policy change, thereby highlighting the value of systemic, analytical approaches to policy-making, while simultaneously emphasizing technology dynamics and complex system interdependencies as key mechanisms that limit targeted policy interventions.

7. Limitations and Future Research

Our study has several limitations that lend themselves as avenues for future research. First, one could argue that the case of the German FIT system for PV is special in that with the development of the FIT policy makers in Germany in many ways treaded uncharted trails. The lack of experience with this instrument might have caused problems and iterations, leading to a strong prevalence of 'compulsive policy-making'. However, there is some indication that in fact countries that implemented FIT schemes at a later point in time – notably Spain, the Czech Republic and Italy – went through similar cycles of policy evolution and sometimes drastically altered policy design in response to the emergence of unexpected issues (del Río González, 2008). To better understand the external validity of the framework proposed in this paper, it would be interesting to juxtapose the evolution of FIT systems in different countries and analyze commonalities in their development.

Second, as pointed out in the previous section, it seems likely that the degree to which policy makers can foresee developments and successfully intervene in a socio-technical system depends on the complexity of the system. Given the strongly international nature of the PV industry and the high dynamic at which it has evolved over the last years, compulsive sequences might be more pronounced for the innovation system for PV than for simpler, geographically bounded systems. Moreover, the observations of compulsive sequences may be specific to interventions in early-stage innovation systems which experience unstable industry structures, fast technological learning and high rates of growth. Future research seems necessary to examine the existence of compulsive policy-making in innovation systems for technologies other than PV.

Third, future studies should investigate to which extent the findings of our analysis for FITs can be generalized to other policy instruments and policy mixes. During our analysis we found that the

German FIT system has been complemented by a number of policy measures, such as demonstration programs, industry policy measures, export initiatives and grid infrastructure incentives. These additional measures very closely followed the prevalent issues in the socio-technical system and – like the FIT – drove their occurrence, which provides some first evidence that our framework might be applicable to other forms of policy interventions and policy mixes.

8. Conclusion

With this paper, we contribute to a better understanding of the dynamics that ensue when policy makers engage as system builders to induce technological change. The literature on innovation systems suggests identifying and removing so-called system failures to foster the development and diffusion of technologies. Currently, however, it remains unclear how complex system interdependencies limit policy makers' ability to purposefully intervene in socio-technical systems. To investigate this question, we studied the evolution of the highly effective and widely copied German feed-in tariff system for solar photovoltaics as a policy instrument targeted at 'market formation'. We find that at each point in time, policy makers in Germany directed their attention to a limited number of issues that were considered particularly important for an efficient deployment of solar photovoltaic technologies. Policy interventions often successfully resolved existing issues, making the German FIT for PV a good example for policy learning. At the same time, however, by inducing technological change, each policy intervention also altered the socio-technical system in a way that brought new issues to the fore. The newly emerged issues subsequently became the target of subsequent policy efforts, leading to a continuous cycle of policy makers inducing and reacting to technological change. In analogy to what Rosenberg (1969) called 'compulsive sequences' we label these cycles 'compulsive policy-making'. Our framework complements existing theories of policy learning by pointing to the important role of complex dynamics of socio-technical systems – particularly technological change – as a driver of policy change. By describing how system dynamics may simultaneously limit and drive targeted policy interventions, our study represents a first step towards a closer connection of the literature on innovation systems with the work on policy learning.

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Appendix

Table A1: List of most important documents.

ID	Date	Translated Document Title	Original Title
D1	24/09/1990	Report by the Enquete Commission “Shaping the technological development: Technological impact assessment and evaluation”: Conditions and consequences of strategies pertaining to building a solar hydrogen economy	Bericht der Enquete-Kommission "Gestaltung der technischen Entwicklung; Technikfolgen-Abschätzung und -Bewertung": Bedingungen und Folgen von Aufbaustrategien für eine solare Wasserstoffwirtschaft
D2	07/12/1990	Legislation on the feed-in of electricity from renewable energies into the public grid (Feed-in law)	Gesetz über die Einspeisung von Strom aus erneuerbaren Energien in das öffentliche Netz (Stromeinspeisungsgesetz)
D3	17/03/1994	Response by the German government to the major interpellation by the Green Party: Success record of the German government with regard to climate protection	Antwort der Bundesregierung auf die Große Anfrage der Gruppe BÜNDNIS 90/DIE GRÜNEN: Klimaschutz-Erfolgsbilanz der Bundesregierung
D4	05/04/1994	Response by the German government to the minor interpellation by the SPD: Future of the solar industry in the Federal Republic of Germany	Antwort der Bundesregierung auf die Kleine Anfrage der Fraktion der SPD: Zukunft der Solarwirtschaft in der Bundesrepublik Deutschland
D5	27/07/1995	Response by the German government to the minor interpellation by the Green Party: Future prospects of the photovoltaic industry in Germany	Antwort der Bundesregierung auf die Kleine Anfrage der Fraktion BÜNDNIS 90/DIE GRÜNEN: Zukunftsperspektiven für die Photovoltaikindustrie In Deutschland
D6	13/10/1995	Legislative draft by the Green Party: Draft of a legislation for the revision of the legislation on the feed-in of electricity from renewable energies into the public grid (Feed-in law)	Gesetzentwurf der Fraktion BÜNDNIS 90/DIE GRÜNEN: Entwurf eines Gesetzes zur Änderung des Gesetzes über die Einspeisung von Strom aus erneuerbaren Energien in das öffentliche Netz (Stromeinspeisungsgesetz)
D7	18/10/1995	Briefing by the German government: Experience report by the German Ministry of Economy on the Feed-in Law	Unterrichtung durch die Bundesregierung: Erfahrungsbericht des Bundesministeriums für Wirtschaft zum Stromeinspeisungsgesetz
D8	26/04/1996	Legislative petition by the Green Party: 10-point plan for entering the solar age	Antrag der Fraktion Bündnis 90/DIE GRÜNEN: 10-Punkte-Programm für den Einstieg ins Solarzeitalter
D9	13/06/1996	Protocol of the German Bundestag, 110 th session, 13 th legislative period	Deutscher Bundestag: Stenografischer Bericht, 110. Sitzung, 13. Wahlperiode
D10	04/12/1996	Response by the German government to the major interpellation by the Green Party: Support of the photovoltaic industry by the German government	Antwort der Bundesregierung auf die Große Anfrage der Fraktion BÜNDNIS 90/DIE GRÜNEN: Unterstützung der Photovoltaik durch die Bundesregierung
D11	01/04/2000	Legislation on the preferential feed-in of renewable energies (Renewable Energy Sources Act – EEG) as well as on the revision of the Energy Industry Act and the Mineral Oil Tax Act	Gesetz über den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz – EEG) sowie zur Änderung des Energiewirtschaftsgesetzes und des Mineralölsteuergesetzes
D12	16/07/2002	Briefings by the German government: Report on the state of market introduction and cost development of plants for the generation of electricity from renewable energies (experience report on the EEG)	Unterrichtung durch die Bundesregierung: Bericht über den Stand der Markteinführung und der Kostenentwicklung von Anlagen zur Erzeugung von Strom aus erneuerbaren Energien (Erfahrungsbericht zum EEG)
D13	23/07/2002	Legislation on the revision of the Mineral Oil Tax Act and other laws	Gesetz zur Änderung des Mineralölsteuergesetzes und anderer Gesetze
D14	31/01/2003	Protocol of the German Bundestag, 23 rd session, 15 th legislative period	Deutscher Bundestag: Stenografischer Bericht 23. Sitzung, 15. Wahlperiode
D15	16/07/2003	First legislation for the amendment of the Renewable Energy Sources Act	Erstes Gesetz zur Änderung des Erneuerbare-Energien-Gesetzes

Table A1: List of most important documents (ctd.).

ID	Date	Translated Document Title	Original Title
D16	10/12/2003	Response by the German government to the major interpellation by the CDU/CSU: Forward-looking and efficient design of the amendment of the Renewable Energy Sources Act	Antwort der Bundesregierung auf die Große Anfrage der Fraktion der CDU/CSU: Zukunftsorientierte und effiziente Gestaltung der Novelle des Erneuerbare-Energien-Gesetzes
D17	12/12/2003	Protocol of the German Bundestag, 83 rd session, 15 th legislative period	Deutscher Bundestag: Stenografischer Bericht 83. Sitzung, 15. Wahlperiode
D18	22/12/2003	Second legislation for the amendment of the Renewable Energy Sources Act	Zweites Gesetz zur Änderung des Erneuerbare-Energien-Gesetzes
D19	12/01/2004	Legislative drafts by the SPD and the Green Party: Draft for a legislation on the revision of the law pertaining to renewable energies in the electricity sector	Gesetzentwurf der Fraktionen SPD und BÜNDNIS 90/DIE GRÜNEN: Entwurf eines Gesetzes zur Neuregelung des Rechts der Erneuerbaren-Energien im Strombereich
D20	21/04/2004	Legislation on the revision of the law pertaining to renewable energies in the electricity sector	Gesetz zur Neuregelung des Rechts der Erneuerbaren Energien im Strombereich
D21	19/10/2004	Major interpellation by the CDU/FDP: Renewable Energies in Germany	Große Anfrage der Fraktion der CDU/CSU: Erneuerbare Energien in Deutschland
D22	16/02/2006	Protocol of the German Bundestag, 19 th session, 16 th legislative period	Deutscher Bundestag: Stenografischer Bericht 19. Sitzung, 16. Wahlperiode
D23	28/09/2006	Protocol of the German Bundestag, 54 th session, 16 th legislative period	Deutscher Bundestag: Stenografischer Bericht 54. Sitzung, 16. Wahlperiode
D24	09/11/2006	Legislative petition by the FDP: Solar Entrepreneurship in Germany – Accepting the challenges, taking the opportunity	Antrag der Fraktion der FDP: Solares Unternehmertum in Deutschland – Herausforderungen annehmen, Chancen nutzen
D25	03/04/2007	Proposed resolution and report by the committee for the Environment, Nature Conservation and Nuclear Safety: Report of the German Energy Agency GmbH (dena) on the state and need for action with regard to the support of the export of renewable energy technologies 2003/2004	Beschlussempfehlung und Bericht des Ausschusses für Umwelt, Naturschutz und Reaktorsicherheit zu der Unterrichtung durch die Bundesregierung: Bericht der Deutschen Energie-Agentur GmbH (dena) über die Bestandsaufnahme und den Handlungsbedarf bei der Förderung des Exportes Erneuerbarer-Energien-Technologien 2003/2004
D26	26/04/2007	Protocol of the German Bundestag, 94 th session, 16 th legislative period	Deutscher Bundestag: Stenografischer Bericht 94. Sitzung, 16. Wahlperiode
D27	09/11/2007	Briefing by the German government: Experience report 2007 on the Renewable Energy Sources Act (EEG experience report 2007)	Unterrichtung durch die Bundesregierung: Erfahrungsbericht 2007 zum Erneuerbare-Energien-Gesetz (EEG-Erfahrungsbericht 2007)
D28	14/02/2008	Protocol of the German Bundestag, 142 nd session, 16 th legislative period	Deutscher Bundestag: Stenografischer Bericht 142. Sitzung, 16. Wahlperiode
D29	18/02/2008	Legislative draft by the German government: Draft of a legislation for the revision of the law pertaining to renewable energies in the electricity sectors and changes of corresponding regulations	Gesetzentwurf der Bundesregierung: Entwurf eines Gesetzes zur Neuregelung des Rechts der Erneuerbaren Energien im Strombereich und zur Änderung damit zusammenhängender Vorschriften
D30	21/02/2008	Protocol of the German Bundestag, 142 nd session, 16 th legislative period	Deutscher Bundestag Stenografischer Bericht 145. Sitzung, 16. Wahlperiode
D31	10/04/2008	Protocol of the German Bundestag, 154 th session, 16 th legislative period	Deutscher Bundestag: Stenografischer Bericht, 154. Sitzung, 16. Wahlperiode
D32	04/06/2008	Proposed resolution and report of the committee for the Environment, Nature Conservation and Nuclear Safety on the legislative draft by the German government on a legislation for the revision of the law pertaining to renewable energies in the electricity sectors and changes of corresponding regulations	Beschlussempfehlung und Bericht des Ausschusses für Umwelt, Naturschutz und Reaktorsicherheit zu dem Gesetzentwurf der Bundesregierung Entwurf eines Gesetzes zur Neuregelung des Rechts der Erneuerbaren Energien im Strombereich und zur Änderung damit zusammenhängender Vorschriften

Table A1: List of most important documents (ctd.).

ID	Date	Translated Document Title	Original Title
D33	01/01/2009	Legislation for the revision of the law pertaining to renewable energies in the electricity sectors and changes of corresponding regulations	Gesetz zur Neuregelung des Rechts der Erneuerbaren Energien im Strombereich und zur Änderung damit zusammenhängender Vorschriften
D34	03/11/2009	Protocol of written questions including answers by the government received from 27 th October to 13 th November 2009	Schriftliche Fragen mit den in der Zeit vom 27. Oktober bis 13. November 2009 eingegangenen Antworten der Bundesregierung
D35	26/02/2010	Protocol of the German Bundestag, 25 th session, 17 th legislative period	Deutscher Bundestag: Stenografischer Bericht 25. Sitzung, 17. Wahlperiode
D36	23/03/2010	Legislative drafts by the CDU/CSU and FDP: Draft of a legislation for the revision of the Renewable Energy Sources Act	Gesetzentwurf der Fraktionen der CDU/CSU und FDP: Entwurf eines...Gesetzes zur Änderung des Erneuerbare-Energien-Gesetzes
D37	25/03/2010	Protocol of the German Bundestag, 34 th session, 17 th legislative period	Deutscher Bundestag: Stenografischer Bericht 34. Sitzung, 17. Wahlperiode
D38	19/04/2010	Reponses by the technical expert Philippe Welter on the list of questions handed in by the parliamentary groups as part of the public hearing of the German parliament – committee for the Environment, Nature Conservation and Nuclear Safety – on the legislative draft by the CDU/CSU and FDP for the revision of the Renewable Energy Sources Act	Antworten vom Sachverständigen Philippe Welter auf die Fragen des Fragenkatalogs der Fraktionen im Rahmen der Öffentlichen Anhörung des Deutschen Bundestages - Ausschuss für Umwelt, Naturschutz und Reaktorsicherheit - zum Gesetzentwurf der Fraktionen der CDU/CSU und FDP zur Änderung des Erneuerbare-Energien-Gesetz
D39	19/04/2010	Reponses by the technical expert Dr. Wolfgang Seeliger on the list of questions handed in by the parliamentary groups as part of the public hearing of the German parliament – committee for the Environment, Nature Conservation and Nuclear Safety – on the legislative draft by the CDU/CSU and FDP for the revision of the Renewable Energy Sources Act	Antworten vom Sachverständigen Dr. Wolfgang Seeliger auf die Fragen des Fragenkatalogs der Fraktionen im Rahmen der Öffentlichen Anhörung des Deutschen Bundestages - Ausschuss für Umwelt, Naturschutz und Reaktorsicherheit - zum Gesetzentwurf der Fraktionen der CDU/CSU und FDP zur Änderung des Erneuerbare-Energien-Gesetz
D40	20/04/2010	Comments by the technical expert Prof. Eicke R. Weber on the public hearing on the legislative draft by the CDU/CSU and FDP for the revision of the Renewable Energy Sources Act in the committee for the Environment, Nature Conservation and Nuclear Safety of the German parliament	Stellungnahme von Prof. Eicke R. Weber zur Öffentliche Anhörung zum Gesetzentwurf der Fraktionen der CDU/CSU und FDP eines Gesetzes zur Änderung des Erneuerbare-Energien-Gesetzes des Ausschuss für Umwelt, Naturschutz und Reaktorsicherheit des deutschen Bundestag
D41	21/04/2010	Committee for the Environment, Nature Conservation and Nuclear Safety: Corrected protocol of the public hearing on the legislative draft by the CDU/CSU and FDP for the revision of the Renewable Energy Sources Act	Ausschuss für Umwelt, Naturschutz und Reaktorsicherheit: Korrigiertes Wortprotokoll Öffentliche Anhörung zum Gesetzentwurf der Fraktionen der CDU/CSU und FDP Entwurf eines ... Gesetzes zur Änderung des Erneuerbare-Energien-Gesetzes
D42	05/05/2010	Legislative petition by the Green Party on the third consultation of the legislative draft by the CDU/CSU and FDP: Draft of a law for the revision of the Renewable Energy Sources Act	Entschließungsantrag der Fraktion BÜNDNIS 90/DIE GRÜNEN zu der dritten Beratung des Gesetzentwurfs der Fraktionen der CDU/CSU und FDP: Entwurf eines ... Gesetzes zur Änderung des Erneuerbare-Energien-Gesetzes
D43	06/05/2010	Protocol of the German Bundestag, 40 th session, 17 th legislative period	Deutscher Bundestag: Stenografischer Bericht 40. Sitzung, 17. Wahlperiode
D44	08/06/2010	Briefing by the German government: Law for the revision of the Renewable Energy Sources Act, call for the conciliation committee	Unterrichtung durch den Bundesrat: ... Gesetz zur Änderung des Erneuerbare-Energien-Gesetzes, Anrufung des Vermittlungsausschusses
D45	07/07/2010	Committee for the Environment, Nature Conservation and Nuclear Safety: Corrected protocol of the public hearing on the legislative draft by the Green Party: Accelerating the nuclear phase-out – Shaping the electricity market in a forward-looking way	Ausschuss für Umwelt, Naturschutz und Reaktorsicherheit: Korrigiertes Wortprotokoll Öffentliche Anhörung zum Antrag der Fraktion BÜNDNIS 90/DIE GRÜNEN: Atomausstieg beschleunigen - Strommarkt zukunftsfähig entwickeln

Table A1: List of most important documents (ctd.).

ID	Date	Translated Document Title	Original Title
D46	11/08/2010	First legislation for the amendment of the Renewable Energy Sources Act	Erstes Gesetz zur Änderung des Erneuerbare-Energien-Gesetzes
D47	28/10/2010	Protocol of the German Bundestag, 68 th session, 17 th legislative period	Deutscher Bundestag: Stenografischer Bericht 68. Sitzung, 17. Wahlperiode
D48	01/12/2010	Protocol of the German Bundestag, 77 th session, 17 th legislative period	Deutscher Bundestag: Stenografischer Bericht 77. Sitzung, 17. Wahlperiode
D49	18/02/2011	Briefing by the German government: Report by the Expert Advisory Board on Environmental Issues: Pathways to 100% electricity generation from renewable energy	Unterrichtung durch die Bundesregierung: Sondergutachten des Sachverständigenrates für Umweltfragen: Wege zur 100 % erneuerbaren Stromversorgung
D50	23/02/2011	Proposed resolution and report by the committee for the Environment, Nature Conservation and Nuclear Safety on the legislative draft by the German government: Draft of a legislation for the implementation of directive 2009/38/EG on the support of the use of energy from renewable sources (EAG EE)	Beschlussempfehlung und Bericht des Ausschusses für Umwelt, Naturschutz und Reaktorsicherheit zu dem Gesetzentwurf der Bundesregierung: Entwurf eines Gesetzes zur Umsetzung der Richtlinie 2009/28/EG zur Förderung der Nutzung von Energie aus erneuerbaren Quellen (Europarechtsanpassungsgesetz Erneuerbare Energien – EAG EE)
D51	24/02/2011	Protocol of the German Bundestag, 93 rd session, 17 th legislative period	Deutscher Bundestag: Stenografischer Bericht 93. Sitzung, 17. Wahlperiode
D52	23/03/2011	Legislative petition of the SPD: On the way towards a sustainable, efficient, affordable and secure energy system	Antrag der Fraktion der SPD: Auf dem Weg zu einem nachhaltigen, effizienten, bezahlbaren und sicheren Energiesystem
D53	01/05/2011	Legislation for the implementation of directive 2009/38/EG on the support of the use of energy from renewable sources (EAG EE)	Gesetz zur Umsetzung der Richtlinie 2009/28/EG zur Förderung der Nutzung von Energie aus erneuerbaren Energien (Europarechtsanpassungsgesetz Erneuerbare Energien – EAG EE)
D53	06/05/2011	Experience report 2011 on the Renewable Energy Sources Act (EEG experience report)	Erfahrungsbericht 2011 zum Erneuerbare-Energien-Gesetz (EEG-Erfahrungsbericht)
D54	08/06/2011	Committee for the Environment, Nature Conservation and Nuclear Safety: Uncorrected protocol public hearing on “Support of renewable energies/energy transformation”	Ausschuss für Umwelt, Naturschutz und Reaktorsicherheit: Unkorrigiertes Stenografisches Protokoll: Öffentliche Anhörung zum Thema „Ausbau der erneuerbaren Energien/Energiewende“
D55	29/06/2011	Proposed resolution and report by the committee for the Environment, Nature Conservation and Nuclear Safety on the legislative draft by the German government for the revision of the law to support the electricity generation from renewable energies	Beschlussempfehlung und Bericht des Ausschusses für Umwelt, Naturschutz und Reaktorsicherheit zu dem Gesetzentwurf der Bundesregierung zur Neuregelung des Rechtsrahmens für die Förderung der Stromerzeugung aus erneuerbaren Energien
D56	30/06/2011	Protocol of the German Bundestag, 117 th session, 17 th legislative period	Deutscher Bundestag: Stenografischer Bericht 117. Sitzung, 17. Wahlperiode
D57	01/01/2012	Law for the preferential Feed-in of Renewable Energies (Renewable Energy Sources Act – EEG)	Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz – EEG)

Table A2: Prevalence of issues over time*.

No.	Issue Category	# Text Elem.	Phase 1							Phase 2				Phase 3							Ph. 4
			<1995	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	
1	Lack of maturity and high cost of PV technology	73	19	12	14						2		2		3	5	4	2	5	5	
2	Lack of mass market for solar PV	35	12	10	13																
3	Insufficient financial incentive for power producers of PV	89	51	7	17	6					2		5								
4	Market power of large utilities	60	6	8	13	4					2			3	4	7	2	9		2	
5	Market support as chance to build PV industry and create jobs	371	20	37	31	3			1		4	18	9	4	31	57	82	11	38	21	
6	Market support as chance to increase exports	108		2	5	1					1	7	1	1	5	40	30	4	10	4	
7	High cost for energy-intensive industry	88									4		4		12	18	13		6	32	
8	High cost for society and rising electricity prices	366		2	9							11	4		22	22	42	5	146	103	
9	Increasing competition from China	76															4	2	63	7	
10	Excess remuneration and windfall profits for PV industry	191														1	5	4	139	42	
11	Risk of losing public acceptance for policy and technology	40													1		1		27	11	
12	Risk of hurting domestic PV industry	234														1	2	2	205	24	
13	Increased power intermittency and power regulation	191	9	2								4	2	1		12	15	2	35	109	
14	Risk of reduced grid stability	262		1								4				7	18	4	90	138	
15	Lack of market integration	166														1	17	3	13	132	

*Note that the length and nature of the identified text elements varies. The count of elements is therefore intended to reveal general trends in issue prevalence rather than their exact importance in a particular year.

International Support for Feed-in Tariffs in Developing Countries – A Review and Analysis of Proposed Mechanisms^{*}

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Abstract

Government support in the form of so-called feed-in tariff policies (FITs), which combine long-term, fixed-price electricity purchase agreements and guaranteed grid-access, has attracted large private-sector investments in sustainable electricity generation in the industrialized world. In an effort to replicate these experiences globally, a number of international organizations, NGOs, banks and donor countries are proposing mechanisms to cover part of the cost of FITs in developing countries. This paper reviews these proposals for supported FITs and then uses a case study of Thailand's Alternative Energy Development Plan 2013-2021 to investigate the opportunities and challenges of supporting FITs at a global scale. The review highlights that these proposed mechanisms foresee different roles for national governments and supporting entities, particularly in terms of who is responsible to balance fixed FIT payments with uncertain revenues and savings from carbon markets, donors and avoided fuel consumption. The case study results then show that the uncertainty about the actual cost of supported FITs is so significant that the responsibility to balance the FIT budget has to be considered carefully in the design of any mechanism that is to be employed at scale. To a considerable extent, the uncertainty is driven by the counterfactual analysis, i.e., by assumptions about the future savings from avoided fossil fuel consumption: for example, depending on the fossil fuel price scenario the FIT may result in a cost of USD 17bn or savings of 23bn. Unlike uncertainty about the necessary level of FIT payments, uncertainty about the avoided fossil fuel cost materializes only over the course of the policy's lifetime, making it politically challenging. This suggests that an international support mechanism that differentiates the allocation of responsibility depending on the income-level of the recipient country is more suitable for global-scale support than a one-size-fits-all approach.

Keywords: Renewable energy, Feed-in tariffs, Development assistance, Developing countries; Climate Policy

1. Introduction

Avoiding dangerous climate change will require a rapid up-scaling and redirection of electricity infrastructure investments. The Intergovernmental Panel on Climate Change projects that the average annual investment in conventional fossil-fuelled electricity generation over the next 15 years will need to decrease by 20% compared to 2010 levels, while annual investment in low-carbon electricity supply will need to rise to around USD 300bn over the same period, about twice the current level [1]. Trends in overall emission growth indicate that an increasing share of these investments will need to flow into infrastructure in developing countries [2]. How the industrialized world can best support developing countries in attracting these investments is therefore keenly debated among researchers and policymakers [3–10].

Much of the global investment in renewable energy in the last decade has been incentivized by so-called feed-in tariff policies (FITs), which combine long-term, fixed-price electricity purchase agreements and guaranteed grid-access. FITs have been especially successful in attracting private-sector investments in new renewable energy technologies, supporting 64% of global wind and 87% of global PV capacity [8]. The United Nations Development Program estimates that by 2012, 66 countries had some form of FIT in place, up from only two countries in 1990, as shown in Figure 1 [11]. More than half of these tariffs have been enacted in the developing world, where renewable energy investments reached USD 112 bn in 2012, representing some 46% of the world total [1-2].

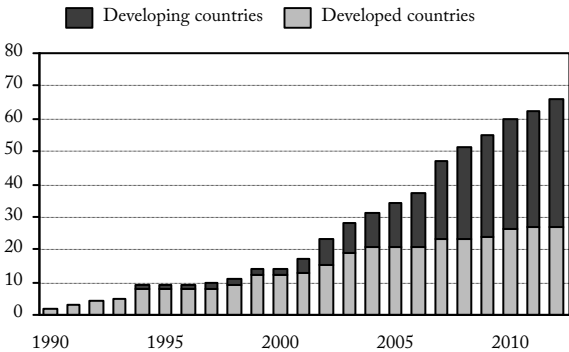


Figure 1: Number of countries with some form of FIT legislation worldwide, 1990-2012 [11].

The finance flows necessary to alter the trajectory of electricity sector investments in developing countries are significant. The United Nations Department of Economic and Social Affairs (UN DESA) estimates that a large-scale rollout of FITs in developing countries would cost about USD 250-270bn per year [13]. Smaller countries in particular often lack the resources to provide sufficiently stable support to attract private sector investments at a large scale. Most of the current investment in

renewable energy in developing countries is thus heavily concentrated, in major markets such as China and India [14]. In an effort to replicate and expand the effects of FITs globally, a number of international organizations, NGOs, banks and donor countries have proposed mechanisms that the international community covers a share of the *incremental cost*⁷⁸, i.e., the cost gap between conventional electricity generation and the FITs in low- and middle-income countries [9,13,15–20].

This paper presents a review and a case study to investigate how FITs in developing countries can be supported internationally. The proposals for “supported FITs” all aim to provide some form of direct international financial transfer to fund FITs in developing countries, but they span a wide range of policy designs, with different administrative forms, responsibilities and tariff structures. Given the size of required commitments, and the long-term nature of payments under FITs, the institutional mechanisms used to allocate and channel international support need to be very well understood before they can be applied on a global scale. However, since most proposals have been formulated in the last four to five years, there has been limited systematic research on supported FITs and how they compare to other forms of international support. For the same reason, there has been little comparative work on the different proposals. To address this gap, this paper first reviews the proposed supported FIT mechanisms, highlighting the ways in which the proposals differ in terms of the roles they assign to the international donors and the national government. In a second step, the paper presents a quantitative case study of a hypothetical internationally supported FIT to finance Thailand’s renewable energy targets for 2021 [21]. The case study illustrates the cost and cost determinants of supported FITs, and suggests that the roles assigned to the international donors and the national government – in particular the responsibility to balance fixed FIT payments with uncertain and volatile revenues and savings – are a crucial design element for internationally supported FITs.

The following section will introduce the different proposals for internationally supported FITs (Section 2). Section 3 introduces the case, followed by section 4 which presents the model, data sources, and methodology. The results of the case study are presented in Section 5, and their policy implications are discussed in Section 6. The main conclusions of the paper are summarized in section 1.

⁷⁸ In this paper “incremental cost” refers to the difference between conventional and renewable electricity in USD/kWh and is used interchangeably with “cost gap” and “additional cost”.

2. International Support Mechanisms for Feed-in Tariffs in Developing Countries

2.1. Scope of Analysis

This paper defines a FIT in accordance with the World Bank as a performance-based support instrument that offers three key incentives to investors in renewable energy projects: a standardized, fixed electricity purchase tariff per kWh, guaranteed purchase of the electricity produced for a specified period, and guaranteed access to the grid [22]. “Standardized” implies in this case that the available tariff is determined administratively at the moment of project installation and defined by project characteristics, notably installation year, quality of the resource, location, technology and size, rather than individually negotiated or determined by market competition.⁷⁹ FITs are generally specified as a regulated purchase obligation on national or regional electric utilities. In addition to the tariffs itself, FIT policies are often complemented by additional incentives in the form of investment grants or low-interest loans [5].

Supported FITs are understood here as mechanisms that aim to *channel international support to directly cover a share of the FIT payments* over the lifetime of the projects. Other means of international support for FITs in developing countries are possible, of course, including technical assistance, grants, loans, financial guarantees, and procedural support, and a number of alternatives to direct FIT coverage have been proposed to support developing countries [4,11,23]. However, these alternatives go beyond the scope of this paper. Furthermore, the presented discussion is limited to FITs for grid-connected policies; proposals for decentralized mini grids supported by FITs are therefore not considered here [24,25].

2.2. Proposed Mechanisms to Cover FIT Cost in Developing Countries

Existing international funding sources have historically neither been large nor flexible enough to support national FITs in a broad and programmatic way [5]. Aiming to alleviate this situation, the ten main proposals for supported FITs, identified by the author and listed in Table , can be classified into

⁷⁹ This definition excludes reverse auctions for purchase tariffs.

three categories (see Figure 2): (1) *globally managed FITs*, which propose global FIT policy regimes that give all developing countries, below certain income or consumption thresholds, the right to opt in to a single, homogenous FIT policy; (2) *domestically managed supported FITs*, which propose ways for heterogeneous, domestically designed and managed FIT policies to access (existing or emerging) international funding sources; and (3) *globally managed incremental FITs*, which propose to upgrade heterogeneous, domestically designed and managed FIT policies through an additional, homogenous global FIT premium, thereby creating, in essence, two parallel FITs which are paid on top of each other.

2.2.1. Globally Managed FITs

Three ambitious proposals link global support for FITs to global technology cost or development targets. The European Renewable Energy Council (EREC) and Greenpeace proposed a scheme, called the “FIT Support Mechanism”, that aims to bring down the electricity generation cost for all renewable energy technologies to a level below that of conventional coal and gas power plants [20]. Under this proposal, a global fund, financed by indicator-based international contributions, would finance the incremental cost of FITs for a broad range of renewable energy technologies to all developing countries that enact a national FIT law “based on successful examples”. Teske et al. [20] estimate that the scheme could cover up to 7,400 TWh of annual renewable electricity generation by 2030, corresponding to roughly 37% of the world’s total generation in 2010 [26], with incremental cost projected to average USD 60-80bn annually from 2010 to 2030.

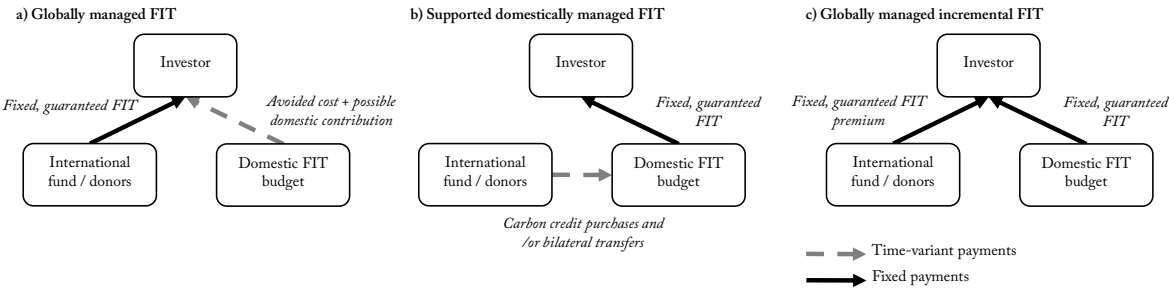


Figure 2: Payment structure of three alternative types of supported FITs.

A similar program was proposed in 2009 by UN DESA, called the Global Green New Deal [18], through which technology-specific FITs are provided to all developing countries until all supported renewable energy technologies have reached a target cost level of USD 0.03-0.05/kWh. Also under the auspices of UN DESA, DeMartino and Blanc discussed the option to provide a “Global FIT” to all developing countries below a certain electricity consumption threshold. The authors estimate that

the cost of reaching this target would peak at around USD 250–270bn (in constant 2010 USD) annually from 2025 to 2030, about twice of the current total development assistance [13]. All three proposals expect income-based contributions by the host countries to the FIT budget, but do not go into detail on how they would be determined.

Although designed initially for a specific country, and without a global goal in mind, the “fossil-fuelled FIT”, proposal by Rickerson and Beukering [17] can also be classified as globally managed FIT mechanism if rolled out on a global scale. Developed for the case of Indonesia, the mechanism aims to make FIT support attractive for energy import-dependent developing countries through an innovative cost sharing approach. The national government pays the electricity producer a variable electricity tariff that is indexed to the price of fossil fuel imports. This domestic contribution is topped up by an internationally supported fund to provide, in sum, a fixed FIT payment stream. The fund can recover its investment if the domestic contribution exceeds the FIT level long enough, after which the savings are passed through to the ratepayers.

2.2.2. Domestically Managed Supported FITs

In contrast to the “top-down” approach of the globally managed FITs, a number of proposals focus on how bottom-up, domestically managed FIT policies can get access to broader, existing or emerging international funding structures, notably bilateral development assistance and carbon markets.

Given the nature of performance-based FIT payments, a number of international donors have emphasized that FIT policies are well suited to be supported by result-based, *bilateral development assistance* [5]. The Norwegian government’s Energy+ initiative, for example, provides funding to the domestic FIT in India on a bilateral basis [27].

Several other proposals explore the option to receive *carbon credits* for national FIT policies under the emerging post-Kyoto regime for the United Nations Framework Convention on Climate Change (UNFCCC). Central to these ideas is the fact that carbon credits are generated on a sectoral basis rather than a project-by-project basis, possibly easing administrative and transaction cost. For example, Burian & Arens [28], Grant [29] and Edkins et al. [30] consider the possibility of financing FITs in South Africa through sectoral carbon credits. The most detailed elaboration on the topic is provided by Okubo et al. [16], who analyzed South Korea’s FIT and suggested that FITs can be supported as a “credited nationally appropriate mitigation action” under the UNFCCC. An alternative is the bilateral carbon market structure that is emerging with Japan’s Joint Crediting Mechanism, under which

bilateral agreements create a regulatory framework that allows a wide range of carbon emission mitigation initiatives to receive carbon credits. A feasibility study explored how to fund part of the cost of Mongolia's FIT, in addition to technological and financial assistance, in return for the carbon credits generated under the program [31].

2.2.1. Globally Managed Incremental FITs

Striking a balance between the approaches presented above, *globally managed incremental FITs* aim to build on domestic FITs and support them with a centrally managed FIT support mechanism that draws on established sources and means of development finance.

The GET FIT program, developed by Deutsche Bank for the Advisory Group on Energy and Climate Change of the Secretary General of the United Nations, is the most advanced of these [9,32,33]. It aims to *up-grade* existing national FIT policies through a country-specific combination of up-front payments, performance-based payments, risk insurances and attractive debt finance conditions. The performance-based payments come in the form of a *fixed tariff premium*, which is paid on top of domestic FITs and aims to close the gap between the cost of renewable electricity and the host country's ability to pay. In essence, the GET FIT program creates a *second FIT policy*, with a tariff that reflects the projected cost gap, in addition to the domestic policy. A version of the GET FIT program is currently being tested in Uganda, where GET FIT upgraded the existing FIT in cooperation with the German development bank KfW [34].

Table 1: Proposed mechanism for internationally supported FITs in developing countries.

Type	Proposal	References / Examples	Eligibility	Domestic contribution	Main international support	Institutional structure of support	Who balances FIT budgets?	Further support
Globally managed FITs	FIT support mechanism (FTSM)	Greenpeace; EREC [20]	Countries which fulfil certain policy and income criteria; environmental criteria for projects	Avoided cost (plus possibly carbon credit sales)	Incremental cost (possibly in part through carbon credit purchases)	Global fund	International side	Additional support for infrastructure cost; debt finance
	Global Green New Deal (GGND)	UN DESA [18]	Countries which fulfil income criteria	Avoided cost (plus possibly indicator-based contribution)	(Remaining) incremental cost	Global fund	International side	Additional financial and technical assistance for least developing countries
	Global FIT (GFIT)	DeMartino & Blanc [13]	Countries below electricity consumption threshold, during 2010-2025	Avoided cost (plus possibly additional contribution)	(Remaining) incremental cost	Global fund	International side	Additional financial for least developing countries
	Fossil-fuelled FIT	Proposal for Indonesia FIT Fund [17]	Countries with high share of commodity-type fossil fuels	Avoided cost	Incremental cost (through variable premium based on fossil fuel price development)	Internationally supported fund for each country	International side	NA
Domestically managed supported FITs	FITs with carbon credits under the UNFCCC	Okubo et al. [16] Burian & Arens [28] Edkins et al. [30]	Countries which fulfil certain policy and UNFCCC criteria	Incremental cost minus carbon credit revenues	Carbon credits purchased at market price	Global carbon market	National government	Diverse
	FITs with bilateral carbon credits	Japan's Joint Crediting Mechanism [31]	Based on bilateral agreements	Incremental cost minus carbon credit revenues	Carbon credits purchased at negotiated price	Bilateral carbon market	National government	Technology, assistance in implementation
	Bilateral assistance to national FITs	E.g., Energy+ initiative [27] supports FIT in India	Bilateral decision	Incremental cost minus bilateral transfers	Negotiated bilateral transfers	Bilateral support	National government	Diverse
Globally managed incremental FITs	Global energy transfer FITs (GET FIT)	Deutsche Bank Climate Change Advisors [32,33]; Rickerson et al. [9]	Small-scale plants in countries which fulfil certain policy and income criteria	Fixed tariff representing projected avoided cost (possibly plus domestic contribution)	Fixed premium equal to projected (remaining) incremental cost	Global fund / Supported national funds	National government and international side	Front-loading ^a ; debt & equity finance; insurance products; technical assistance
	Green Climate Fund Private Sector Facility (GCF PSF)	Green Climate Fund business model framework [37]	Small and medium-sized projects in low-income countries	Fixed tariff representing projected avoided cost (possibly plus domestic contribution)	Fixed premium equal to projected (remaining) incremental cost	Global fund	National government and international side	Insurance products
	Global REFIT Facility under the GCF PSF	World Future Council [15]	Countries which fulfil certain policy and income criteria	Fixed tariff representing projected avoided cost (possibly plus domestic contribution)	Fixed premium equal to projected (remaining) incremental cost	Global fund in cooperation with national funding entities	National government and international side	Additional financial assistance

^aFront-loading refers to a FIT payment structure under which a certain share of the tariff payments is paid upfront, rather than on an annual basis, to the investor to reduce capital expenditures.

Other proposals envision a FIT-specific facility under the Green Climate Fund (GCF), which will manage the annual USD 100bn pledged to be transferred each year to developing countries from 2020 onward under the UNFCCC [15,19,35,36]. The most elaborate scheme, prepared by Michaelowa and Hoch for the World Future Council, calls for the GCF to elicit applications from bottom-up, domestically designed FITs that would be supported by a centrally managed FIT fund. Through this centrally managed fund, the Renewable Energy FIT Facility, the GCF would then subsidize developing countries with an income-dependent share of the cost gap of national FIT policies, in the form of a tariff premium paid on the domestic FIT, together with concessional loans and grants. Under one proposed option, least-developing countries would receive 100% of the projected cost gap between fossil and renewable generation, estimated to range between 2-4 c€/kWh, or 2.76-5.52 cUSD, while medium-income and advanced developed countries would be supported with 50% and 20%, respectively. The authors estimate their proposal to cost USD 1.3bn per year for a program that supports 100GW of new installations annually [15]. In its recently published business model framework, the GCF itself considers funding incremental FITs for small to medium scale renewables in low and medium income countries as one opportunity for its private sector facility (without going into much further detail) [37].

2.3. Three Ways to Balance the FIT Budget

The most important factors that make FITs an attractive policy for investors in the developed world are stable revenue streams for built projects and predictable FIT levels for new projects [38]. All of the reviewed proposals aim to replicate this stability and certainty for investors in developing countries, and share the fundamental FIT design features. In fact, many of the proposed mechanisms explicitly build on each other. Crucially, however, the three categories of supported FITs differ in how the payments are structured, and how the payment structure in turn shapes the roles of international supporters and the national government (see Figure 2). In particular, the proposals differ in how the FIT budget is balanced, i.e., how the responsibility to maintain investment security over the full lifetime of the policy is allocated between the developing country government and the international side. “Balancing the FIT budget” is understood here as balancing fixed FIT payments with uncertain and volatile revenues and fuel cost savings to ensure stable income streams for built projects and predictable FIT levels for new investors. The essential question is: which side is covering the uncertainty in the development of incremental cost over time?

Globally managed FIT mechanisms directly guarantee the full required FIT to the investor (see Figure 2a). The international side thus buffers volatile revenues from carbon credit sales and savings from avoided fossil fuel consumption, and has to adjust its contribution to the incremental cost if projected FIT payments do not match actual revenues and savings. The domestic contribution to the incremental cost, on the other hand, is set ex-ante and by design isolated from any uncertainty about the future development of the incremental cost. EREC and Greenpeace's proposal, for example, suggests that the domestic contribution consists of carbon credit sales and the avoided cost, with the latter being determined according to the "German model". In this model the avoided cost is recovered for the FIT budget by centrally collecting the renewable electricity and selling it on the wholesale market [20].⁸⁰ Rickerson and Beukering's [17] proposal directly links the domestic contribution to a fossil-fuel price index. In both cases, the domestic contribution to the incremental cost is controlled by linking the domestic payments to the *actual* revenues and savings.

Domestically managed supported FITs, in contrast, represent FIT policies in which the national government guarantees the full FIT and is solely responsible for balancing uncertainty in carbon markets as well as donor commitments (Figure 2b). Under globally managed incremental FITs, finally, the international side provides a *fixed premium* on a *fixed domestic FIT*. Since both tariffs are fixed at the beginning of the policy, neither side absorbs the full incremental cost uncertainty; rather, the cost uncertainty over the lifecycle of *built projects* is absorbed by the national government, while the cost uncertainty for new projects over the lifecycle of *the policy* is absorbed by the international side (Figure 2c).⁸¹ Table 2 summarizes how variable revenues and savings affect national governments and international donors in different types of supported FITs.

⁸⁰ The UN DESA proposals also assume that developing countries cover the actual avoided cost, although the documents leave open how they would be determined in the case of implementation.

⁸¹ Deutsche Bank's GET FIT and the GCF proposal [81] each contain provisions to insure the domestic contribution against a default. However, the international contribution is under normal circumstances limited to the fixed premium, while the national government's contribution varies over the lifecycle of the projects with volatile fossil fuel prices.

Table 2: Impact of variable revenues and savings on national governments and international donors.

Type	Impact of time-variant donor contributions, carbon credit revenues and avoided cost savings over time on ...	
	... international side	... national government
Globally managed FIT mechanisms	Global fund directly guarantees stable FITs and balances uncertain and volatile revenues and savings	No direct impact, but may be required to increase contribution over time
Domestically managed supported FITs	No direct impact, but may be required to increase contribution over time	National government directly guarantees stable FITs and balances uncertain and volatile revenues and savings
Globally managed incremental FITs	Built projects: no direct impact New projects: Global fund could adjust the FIT premium over time	Built projects: National government balances tariff with uncertain and volatile revenues and savings cost over the project's lifetime New projects: if global fund does not adjust FIT premiums to changes in incremental cost, the national government would need to raise its payment beyond avoided cost to maintain attractive FIT

It is important to note that there is no systematic difference between the three types as to how much of the *projected* cost is covered by either side. All contain provisions for the host country to cover the avoided cost, and many foresee some form of local contribution to the incremental cost. The difference is in how volatile and uncertain revenues and savings are buffered and balanced. In fact, the clear boundaries between the three categories would blur in a world with perfect foresight of the future cost of renewable and fossil electricity, carbon price trends and donor commitments. Since these cost and price trends are uncertain, however, and the entity that balances the FIT budget shoulders the risk of unforeseen cost developments, the allocation of budget-balancing responsibility between the international and national sides affects the degree of security that the FIT can provide to investors.

The uncertainty in the incremental cost implies that in order to ensure investment security, the budget-balancing responsibility has to be allocated in a way that reflects each side's political and financial capital to support the FIT. It also implies that the degree of uncertainty about the actual incremental cost is as important for the political feasibility of the policy as the overall magnitude of involved commitments. The quantitative case study presented in the following sections therefore explores both the overall magnitude of the incremental cost and the impact of cost uncertainty on the national and international sides under the three different supported-FIT designs.

3. Thailand's Alternative Energy Development Plan

3.1. Electricity Sector Background

This paper presents a quantitative case study of Thailand's electricity sector, which assumes that the country's renewable energy targets for 2021, specified in the Alternative Energy Development Plan (AEDP) [21], are achieved with the help of an internationally supported FIT.

Thailand was chosen as case study because its electricity sector is representative of many middle-income countries in three significant ways. First, the country's electricity is mainly produced from fossil fuels. As of 2011, the electricity sector is dominated by natural gas (67%), with lignite and hard coal providing together an additional 20%. Besides large hydropower (5%), renewable energy constitutes only a small fraction of the electricity mix, mostly in the form of biomass (1.4%) [39]. Second, the country is witnessing a rapid growth in energy demand. A country of 66.9 million with a GDP per capita at USD 5,210, Thailand's primary energy consumption has almost tripled from 1990 to 2011, making it the second-largest energy consumer in the Association of Southeast Asian Nations (ASEAN), while its carbon emissions have grown by 177.5% over the same period.⁸² Electricity generation reached 162 TWh in 2011, up from 29 TWh in 1987, and is projected to double yet again by 2035 [39–41]. Third, like many other middle-income countries, Thailand is increasingly dependent on fossil fuel imports. The country is a net importer of oil, gas and coal, with imports projected to increase to about 90% of consumed oil and gas by 2030 [41]. Nakawiro et al [42] estimate that gas and coal import cost will rise as share of GDP from 0.92% in 2011 to 2.19-2.69% in 2025, depending on the development of fuel prices in the region.

All three factors have particular implications for the calculation of the incremental cost of renewable energy, and are thus relevant to the potential of the case study's results to inform a possible global application of internationally supported FITs. The dependence on fossil fuels makes the savings from avoided fossil fuel consumption the most important factor in the calculation of avoided cost, while rapid demand growth introduces uncertainty into the calculation of avoided cost of conventional generation, because assumptions have to be made about the impact of renewable energy diffusion on

⁸² The power sector is the largest carbon source, with a share in national emissions that grew from 33% in 1990 to 42% in 2011.

the construction of new fossil fuel power plants. Lastly, import dependence implies that the avoided costs are determined by international energy commodity prices, which tend to be more volatile than domestic fossil fuel sources, especially lignite and natural gas.

3.2. Renewable Energy Targets and Current Policy Support

An additional reason to select Thailand as a case study for a supported FIT is that the country has ambitious goals for renewable electricity, but still faces challenges in providing an integrated, stable regulatory framework to achieve these targets [43].

Thailand’s electricity sector planning officials have begun to consider renewable energy as a significant source of electricity generation. The country first formulated its ambitious renewable energy goals in the AEDP of 2012. Updated in 2013 and now aiming to increase the renewable energy in the power sector to 14 GW by 2021, or 24% of the total capacity, the plan is expected to be integrated in the country’s overall electricity sector plan over the course of 2014 [44,45]. As shown in Figure 3, the largest part of renewable capacity is projected to come from biomass (4.8 GW), followed by biogas (3.6 GW), solar power (3 GW), wind power (1.8 GW), municipal solid waste (400 MW) and micro hydro (324 MW). The largest relative increase is targeted for biogas (17-fold) and wind energy (15-fold). It is notable that large hydro is not part of the AEDP. For simplification, we therefore use the term ‘renewable electricity’ in this paper to refer to non-large-hydro renewable electricity technologies.

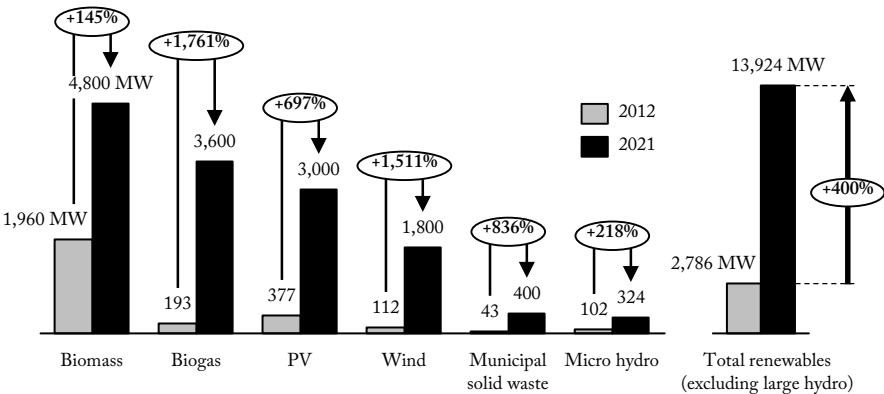


Figure 3: Targets for renewable electricity under Thailand’s Alternative Energy Development Plan; data for 2012 are from DEDE [64]; updated targets for 2021 from Kamolpanus [44].

The policies and regulatory framework to support these ambitious targets are still in flux. In addition to tax incentives and investment grants, the primary government policy to induce renewable energy investments is a FIT premium scheme, referred to as *FIT adder*, under which technology-specific premiums are paid on top of the (variable) wholesale electricity price [43,46]. One of the first

developing countries to introduce a FIT program, Thailand implemented preferential grid-connection and avoided-cost tariffs in 2002, followed by technology-specific FIT premiums in 2006 [43]. The FIT adder program offers investors a power purchase agreement under which fixed premiums, dependent on technology, capacity and project location, are paid on top of a base tariff that is determined by the utility's avoided cost. The FIT adder has been quite successful in attracting private sector investment, but has experienced cycles of boom and bust of applications, fuelled in part by speculation on the value of land with issued licenses for renewable installations [43]. A significant share of issued solar licenses has since been revoked [47]. In 2010, Thailand's government announced plans to transform the FIT adder into a FIT with fixed payments, but has done it so far only for rooftop solar PV [44].

4. Methodology

4.1. Framework of Analysis

A two-step methodology was employed to investigate the overall magnitude of the incremental cost of the AEDP targets and the impact of incremental cost uncertainty on the national and international sides under the three different supported-FIT designs.

First, a bottom-up, techno-economic model was developed to identify the incremental policy cost and the main cost drivers (details in sections 4.2 and 4.3). The model focuses on six renewable energy technologies: biomass, biogas, micro-hydro, on-shore wind, solar PV, and concentrating solar power (CSP).⁸³ Figure 5 in the appendix depicts the overall structure of the model with its key variables and relationships. Two main model outcome metrics are used to assess the policy support needed to achieve Thailand's renewable electricity targets: the *incremental policy cost* as a proxy for marginal social cost [48,49], calculated as cumulative difference between the total cost of renewable electricity generation and the cost of avoided fossil electricity; and the *abatement cost*, i.e., the incremental cost divided by the reduction of carbon emissions resulting from the AEDP.

The impact of different policy design options was then analyzed in a second step by estimating the changes to cost commitments from the national and the international side under different cost trends

⁸³ Municipal solid waste was not considered because of a lack of data on technology choice and cost in Thailand.

and assumptions. To gauge the uncertainty about the level of required *FIT payments* a sensitivity analysis was used (all major input values were varied by $\pm 20\%$). The uncertainty about the *avoided cost* was estimated using different counterfactual scenarios in the form of alternative fossil fuel price assumptions, fossil fuel price trends and methodologies to calculate the avoided cost (see section 4.3).

4.2. Cost of FIT Payments

The electricity generated by each source of renewable electricity is a function of the diffusion path (in GW installed each year) and the plant utilization (in GWh produced per GW of installed capacity each year). Since the AEDP does not contain interim targets, the diffusion of the six considered technologies was modeled as a linear increase in installed capacity over the period 2013–2021.⁸⁴ All renewable electricity is assumed to be fed into the grid, so the plant utilization is a function only of the resource potential. In the case of micro hydro, biogas and biomass, for which significant domestic experience exists, the capacity values were taken from domestic academic sources [50–52]. For wind, solar PV and CSP the capacity factors were estimated using resource information from the IRENA global atlas [53].

To model the FIT payments per unit of electricity produced, it was assumed that the government supports each investment with an inflation-adjusted FIT over 20 years, resulting in FIT payments over the period 2013–2040 for the investments in 2013–2021. The FIT rates for each technology are assumed to exactly reflect the technology's LCOE, or levelized cost of electricity for investments at any point between 2013 and 2021 [23]. An additional 0.0115 USD/kWh were added to the LCOE to account for balancing and grid integration cost of variable renewable energy technologies (PV, CSP and wind) [54]. Table 3 and Table 7 in the appendix provide an overview of input parameters used to calculate the LCOE for the six renewable energy technologies as well as key sector-wide assumptions used in the model.

4.3. Avoided Cost

To model the effect of renewable energy diffusion on conventional electricity generation, we compared the hypothetical scenario without renewable energy diffusion to the case of full implementation of the

⁸⁴ The split between PV and CSP in the (un-differentiated) total solar target is assumed as a relation of 9: (PV) to 1 (CSP).

AEDP targets. The total avoided conventional electricity was then calculated by aggregating the differences between total generation in 2013-2040 with and without AEDP targets for each of the dispatchable technologies (generation from non-dispatchable technologies is not affected by the AEDP).

4.3.1. Fuel Mix Model

Thailand's electricity sector is partly vertically integrated and dominated by state-owned enterprises [55]. The Electricity Generation Authority of Thailand is the transmission system operator, but also operates around 50% of the generation assets directly and controls, as their largest shareholder, the two largest independent power producers. Furthermore, the wholesale market is not liberalized. Decisions over new power plant investments are therefore still made based on long-term integrated plans, rather than purely based on market signals, and plant utilization is based on long-term allocations rather than marginal cost of generation.

The model aims to capture this decision-making process when calculating the fuel mix. The power plant pipeline was taken from the current Power Development Plan (PDP), published in June 2012 [40]. The model builds additional power plants in the sequence determined by the PDP whenever dependable capacity does not exceed peak demand by at least 15%, reflecting the reserve margin required by electricity sector planners [40], or total expected demand exceeds expected generation, based on historic capacity factors, by more than 5%. An exception was made for all hydro power, combined-heat-and-power, and contracted import capacity, which were assumed to come online as planned. This approach is similar to the one adopted by domestic researchers [56]. The dependable capacity equals the total capacity adjusted by factors that aim to reflect the fact that not all built capacity can be expected to be available in the moment of peak demand, because of maintenance, failures, or intermittent generation.⁸⁵ The fuel mix was then calculated, on a yearly basis, from historic capacity factors, marginally adjusted for the dispatchable plant fleet to exactly meet yearly demand. 'Dispatchable' here refers to the plants that are ramped up and down to balance demand, i.e., the full fleet excluding renewables, contracted import capacity (lignite and hydro), municipal solid waste and (heat-led) cogeneration.

⁸⁵ The factors were taken from Sangarasri-Greacen and Greacen [56] and Naksrisuk and Audomvongseree [68].

4.3.2. The Cost of Avoided Electricity

Modeling the marginal cost of avoided electricity required differentiating the impact of renewable capacity installations on fossil generation capacity. This impact can be twofold: plant utilization of dispatchable power plants can be reduced, or the construction of new power plants postponed. The model accounted for these two effects by dividing the total avoided electricity into *operating margin* and *build margin*. For all displaced electricity, the cost of electricity was calculated as LCOE. However, in the case of reduced plant utilization, the *operating margin*, we assumed the marginal cost of electricity to contain only the variable cost (O&M and fuel). The displaced electricity from postponed power plants, the *build margin*, contains all fixed and variable cost.⁸⁶ All input assumptions for the conventional electricity LCOE calculations are summarized in Table 5 in the appendix.

4.4. Avoided Cost Scenarios

In total, 11 models were specified to analyze uncertainty in the avoided cost. Nine models estimate the impact of different assumptions about fossil fuel prices and price trends (M₁₋₉). These nine specifications represent the combination of three different assumptions about the *price per unit of avoided natural gas consumption* and three different *fossil fuel price trends* (3 x 3 price scenarios). When making assumptions about the price of natural gas in the displaced electricity, it is important to note that natural gas in Thailand, as in the rest of the world, is not priced uniformly.⁸⁷ Which type of natural gas is displaced by renewables therefore greatly affects the incremental cost. To analyze this effect, models were calculated using the average price, the average import price, and the average LNG import price. The three fossil fuel price trends were taken from the International Energy Agency [57]. The two remaining specifications, M₁₀₋₁₁, estimated the impact of two alternative assumptions on the degree to which renewables delay new fossil power plants. The standard specification assumes that the displaced electricity is a mix of operating and build margin (see section 4.3.2). Greenpeace's proposal [20], however, determines the avoided cost using the German model, i.e., through wholesale electricity prices, which typically only reflects operating cost. This implies that all displaced electricity is

⁸⁶ This procedure was also employed by Schmidt et al. [48] and is related to the rules employed to calculate avoided carbon emissions in the Clean Development Mechanism under the UNFCCC.

⁸⁷ The average price overall is about 7 USD/MBTU, the average import price about 8.4 USD/MBTU and the average price of imported liquefied natural gas (LNG) about 14.6 USD/MBTU [78].

calculated as operating margin. The opposite assumption is made in the proposal by UN DESA [13], which assumes that all displaced electricity would have to come from new power plants – and therefore contains both capital and operating cost. Models M₁₀₋₁₁ estimate the impact of these alternative assumptions.

5. Results

5.1. Incremental Cost of and Cost Drivers of FIT Policy

The AEDP capacity targets will, if implemented as planned, lead to a significant transformation of Thailand’s electricity sector. The model predicts that the new capacity installed under the AEDP will increase the share of renewable energy generation, excluding large hydro, in the electricity mix from less than 1% to 24% in 2021 (see Figure 4). Over the entire policy lifetime, the AEDP will reduce carbon emissions by some 457 million tons CO_{2eq}.

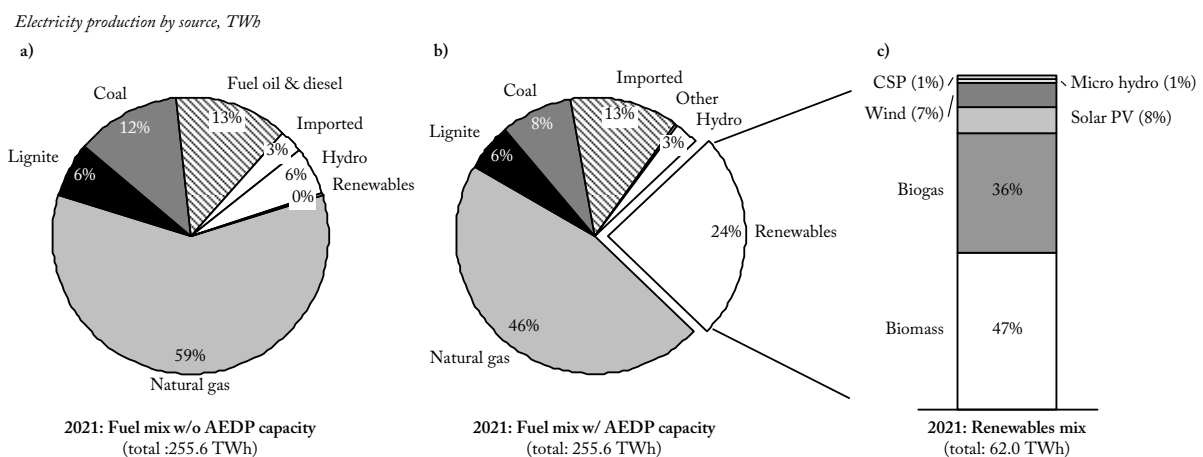


Figure 4: Change in fuel mix through the AEDP: a) fuel mix in 2021 without any new renewable installations after 2012; b) fuel mix in 2021 with AEDP targets; c) shows the renewable generation in 2021 with the AEDP targets in detail.

FIT payments of USD 87.66bn, or 68.34bn in discounted terms⁸⁸, are needed to finance this rise in renewable electricity generation. This translates into an abatement cost of USD 36 per ton of CO_{2eq} in discounted USD₂₀₁₂. The payment streams for all technologies for the period 2013-2040 are displayed

⁸⁸ Discounted to the year 2012 with the yield of 40-year Thai government bonds (4.43%), which reflects the refinancing cost of the Thai government over the period of the assumed FIT payments.

in Figure 5, together with the avoided cost over the same period. Aggregated over all six renewable technologies, FIT payments rise linearly to USD 4.38bn in 2021 and stay stable until 2032, before falling to zero in 2041, when the last plant installed under the FIT goes offline. The avoided cost is USD 66.46bn, or 51.84bn in present value. Over time, the avoided cost follows a similar path, with some volatility, reaching a maximum of USD 3.74bn in 2027 in the standard model specification M₁. Subtracting these from the FIT cost leaves an incremental cost of USD 21.20bn (discounted: 16.50bn). The incremental cost peaks at USD 1.18bn in 2026 and remain positive over the entire policy lifetime. On average, the FIT policy costs an additional USD 0.76bn per year, which corresponds to an average incremental cost of cUSD 2.2 per kWh of renewable electricity.

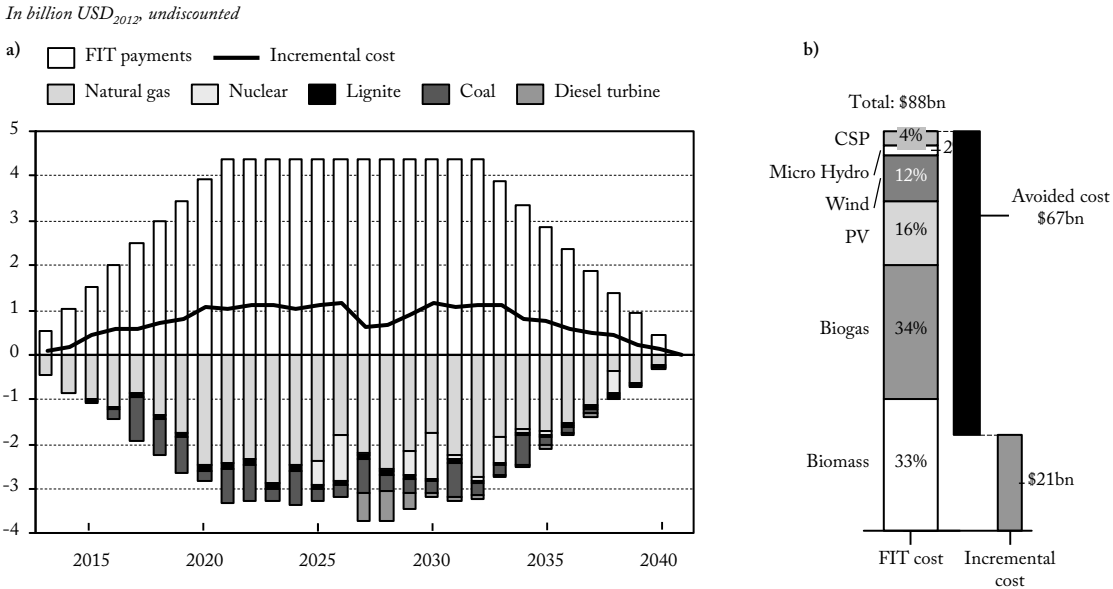


Figure 5: a) Assumed FIT payments (positive), avoided cost (negative) and resulting incremental cost under the AEDP 2013-2040; b) total FIT cost, avoided cost and incremental cost, 2013-2040.

The LCOE by technology are displayed in Figure 6 for the period 2013-2021. Benefiting from global learning effects, the costs of all renewable technologies decrease over time. The decrease is strongest for CSP (35%) and PV (32%) and weakest for biomass (2%). Nevertheless, CSP, PV, wind and micro hydro are more expensive than the main fossil technologies and remain so until 2021. Biomass and biogas are in the same range as most fossil fuel technologies, costing 8.2 cUSD/kWh and 6.9 cUSD/kWh in 2021, with only subcritical lignite and subcritical coal power plants being significantly cheaper. These LCOE trends are reflected in each technology’s contribution to the FIT cost. As shown in Figure 4, biomass and biogas together account for 83% of renewable generation, but only 67% of the FIT payments (see Figure 5). PV and wind are responsible for 8% and 7% of generation,

respectively, while receiving 16% and 12% of the payments. CSP and micro hydro also receive a significantly larger share of FIT payments (4% and 2%) than they contribute to generation (1% each).

As can be seen when comparing Figure 4a and b, the additional renewable generation displaces mostly coal (-4%) and natural gas (-13%). The avoided costs thus comes primarily from avoided natural gas consumption (71% of avoided cost), followed by coal with 16% and nuclear with 7%. This illustrates that the chosen mix of renewable energy and the type of displaced electricity are the most important drivers of the incremental cost.

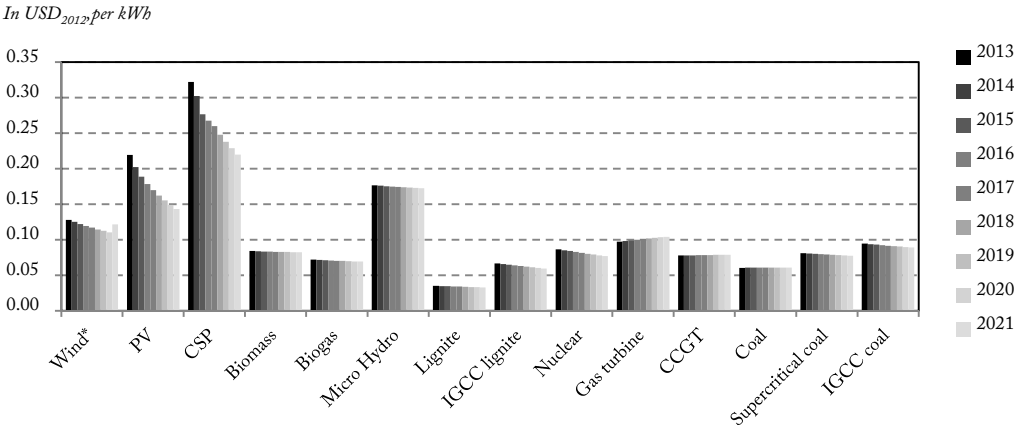


Figure 6: Trends in LCOE for six modeled renewable energy technologies and main fossil fuel alternatives 2013-2021 (avoided cost scenario specification: M1); *the reason for the increase in wind LCOE in 2021 is that the best wind resources will be exhausted by then.

5.2. Uncertainty of Incremental Cost

This section explores how sensitive the incremental cost calculations presented above are to input assumptions. The results for FIT payments, avoided cost and incremental cost in section 5.1 are based on the baseline model specification M₁, which assumes standard assumptions for renewable energy cost, average natural gas prices, IEA’s “current policy” fuel trends, and a mix of operating and build margin in the avoided cost. Figure 7 shows the impact of changes in renewable cost assumptions, while Figure 8 displays results for the different avoided cost scenarios.

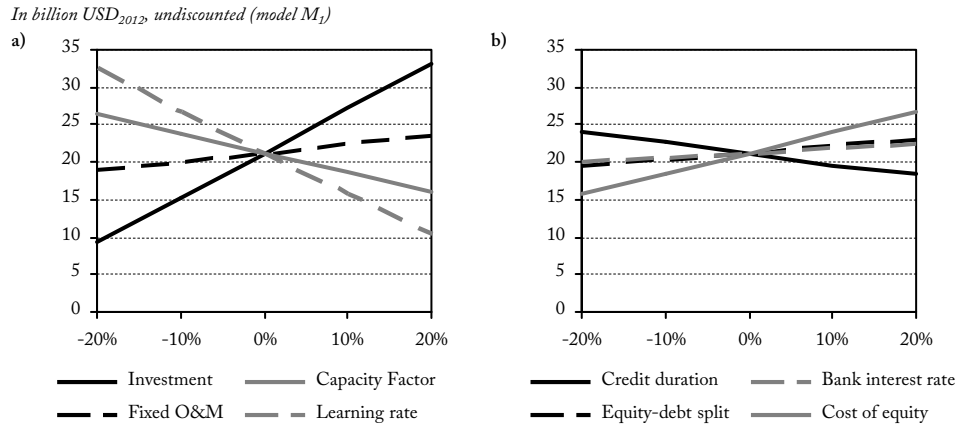


Figure 7: Sensitivity of incremental cost to renewable energy input parameters.

The results suggest that the incremental cost is most strongly affected by changes in the investment cost of renewable technologies (2.8% change in incremental cost per 1% change of diffusion) and the learning rate (2.7%). Although smaller in magnitude, the incremental cost is also sensitive to the capacity factor (1.2%) and the cost of equity (1.3%; shown in Figure 7b). The incremental cost is less sensitive to changes in the fixed operation and maintenance (O&M) cost, bank interest rate, debt-equity split and the credit duration.

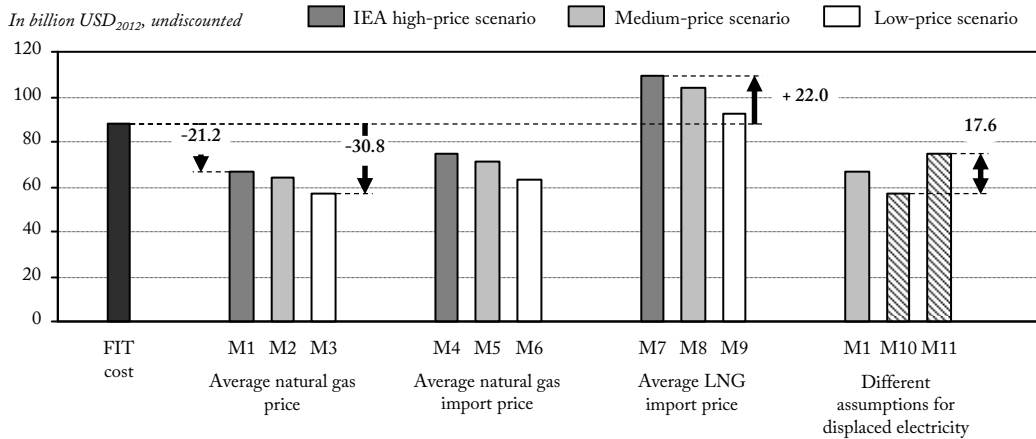


Figure 8: Avoided and incremental cost in different fossil-fuel cost scenarios.

As shown in Figure 8, the differences between avoided cost scenarios have an even stronger impact than the renewable cost parameters. If it is assumed that the displaced natural gas consumption is priced at the average natural gas price (model M₁), the avoided cost are USD 66.46bn; if it assumed that imported natural gas is displaced first (M₄), the avoided cost reach USD 74.51bn, which reduces the incremental cost by 38% to USD 13.15bn. If it is assumed that the avoided electricity would have been fueled by liquefied natural gas (M₇), the avoided cost rise to USD 109.64bn, which translates into

negative incremental cost, or savings, of USD 21.98bn. Although weaker, the different fuel price trend scenarios also have an impact on the incremental cost, as shown for M₂₋₃, M₅₋₆, and M₈₋₉. The difference between the high and low fossil-fuel price scenarios of the IEA is about USD 9bn, corresponding to about 45% of the incremental cost in the standard model specification, and roughly constant across the three sets of models. Finally, the impact of the assumption whether new or existing power plants are displaced, modeled in M₈ and M₁₁, can change the incremental cost by as much as USD 17.6bn. Overall, these results imply that the uncertainty about the incremental cost is driven, to a large extent, by the counterfactual, i.e., by the questions which fossil fuels are displaced, from which type of plants, and at what price.

5.3. Impact of Uncertainty Under Different Supported-FIT Designs

The different types of supported-FIT designs allocate the cost uncertainty differently between the national and the international side. Table 3 shows the share of incremental cost covered by each side under the three alternative supported-FIT designs when investment costs are varied by $\pm 20\%$ and fuel prices follow the two extreme scenarios M₇ and M₃.

Table 3: Impact of incremental cost uncertainty on international and domestic cost under different FIT designs

Model / scenario	Total incremental cost (USD bn)	Incremental cost covered by international side / domestic side (USD bn)		
		Globally managed FIT, with domestic contribution limited to avoided cost	Domestically managed supported FIT; carbon credits and transfers cover projected total incremental cost	Globally managed incremental FIT; international premium covers projected incremental cost of each project
Standard specification: M ₁	21.20	21.20 / 0.00 ^a	21.20 / 0.00 ^a	20.26 / 0.94 ^{ab}
High investment cost (+20%)	33.07	33.07 / 0.00	21.20 / 11.87	32.13 / 0.94
Low investment cost (-20%)	9.33	9.33 / 0.00	21.20 / -11.87	8.39 / 0.94
High fuel prices (M ₇)	-21.98	-21.98 / 0.00	21.20 / -43.18	-21.77 / -0.21
Low fuel prices (M ₃)	30.78	30.78 / 0.00	21.20 / 9.58	27.21 / 3.57

^aOther initial splits of incremental cost between the national and the international sides are possible, of course, but they do not affect the impact of uncertainty as long as the payment structure and the fundamental principle of uncertainty allocation is maintained; ^bThe domestic contribution is positive because on average the cost of electricity decreases over time, due to learning effects and a decreasing share of displaced build margin.

Under a *globally managed FIT* the international side would cover all changes in incremental cost. If the domestic contribution is limited to the real avoided cost, the international contribution in the four

considered cases would range between savings of USD 21.98bn and a cost of 30.78bn. Under a *domestically managed supported FIT* that receives international funds from the carbon market and/or pre-negotiated bilateral transfers, the four scenarios would, *ceteris paribus*, lead to changes in domestic costs ranging between a savings of 43.18bn and cost of 11.87bn (for purposes of simplification, the international contribution is assumed here to cover exactly the projected total incremental cost⁸⁹). In the case of a *globally managed incremental FIT*, both sides are affected by the uncertainty. If each project receives a FIT equaling the current average avoided cost from the domestic government and the remaining gap to the LCOE as a FIT premium from the international side, the cost coverage in the standard specification would be USD 20.26bn and 0.94bn, with variation from -21.77bn to 32.13bn and -0.21bn to 3.57bn, respectively.

6. Discussion

The following discussion is split into two parts. The first part discusses the results of the quantitative case study and puts the numbers into perspective (section 6.1) The second part explores the policy implications of the paper's results, including the findings from the review of proposals in section 2 and the quantitative case results in section 5 (section 6.2). The section closes with a discussion of the paper's limitations (section 6.3).

It has to be noted that the following discussion is limited to FITs as a policy option and does not discuss in detail the relative merits of FITs compared to other policy instruments aimed at promoting emission reductions in general, or low-carbon electricity in particular.

6.1. Incremental Cost of Supported FITs

6.1.1. Magnitude of Incremental FIT Cost

The case study of Thailand's AEDP yields similar results to the global estimates of the incremental cost of supported FITs [13,15,20]. At an average of cUSD 2.2 per kWh over the period 2013-2040 in

⁸⁹ If the carbon credits are sold on a carbon market, the carbon price creates an additional source of uncertainty in the incremental cost. This uncertainty is not explored in more detail here but needs to be considered by policymakers.

the standard model specification, the incremental cost of Thailand's AEDP targets are in the cost range of estimates such as the c€ 2-4 per kWh calculated by Michaelowa and Hoch [15] and the premiums of cUSD 1-2 per kWh paid by the GET FIT pilot in Uganda [34].

The mitigation cost of USD 36 per ton of CO_{2eq} is slightly higher than the 23.1 calculated by Teske et al. [20] but, again, in the same order of magnitude. It is also more than the value of the carbon credits yielded under the Clean Development Mechanism, even when their price peaked in 2008, which means that it is highly unlikely that carbon credits under the current international climate policy regime would be sufficient to fully cover the incremental cost of a supported FIT.

When the results for the Thailand case are extrapolated to all non-OECD countries, supporting the same share of total electricity generation (24%) in 2021 across the Global South would cost some USD 80bn per year, which is in the same order of magnitude as estimates by the European Renewable Energy Council and Greenpeace (although they assume a higher share of supported generation) [20]. Notably, this figure is in the same range as the *total* global official development assistance flows of USD 127bn in 2010 [58]. Given these large funding needs, any proposed mechanism to allocate and guarantee national and international commitments must pay great attention to minimizing cost and uncertainty.

6.1.2. Uncertainty in Incremental Cost

The uncertainty in incremental FIT cost consists of two parts that must be discussed separately. Existing studies have focused on the uncertainty about the level of FIT payments required to attract a given amount of renewable capacity [13].⁹⁰ In the case of Thailand, this uncertainty is driven largely by the investment cost, learning rate, capacity factor and cost of equity. Although significant, uncertainty about the FIT payments does not affect the commitments ex-post; rather, it is resolved in the moment of investment, because the FIT rates are fixed for the full lifetime of the project. (Uncertainty in the O&M cost, which was also identified as an important factor in the sensitivity analysis, is shouldered by the investor). This part of the incremental cost uncertainty can therefore be resolved and managed with the existing FIT policy design toolbox: feasibility studies, pilot FIT projects or regions, expert elicitations, and frequent rate-setting reviews [5]. It does put the overall targets of the policy at risk

⁹⁰ Although not explicitly considered here, the uncertainty about how much capacity investment can actually be attracted per year also falls into the 'ex-ante' category of uncertainty.

because escalating incremental cost might jeopardize political legitimacy in the long run, but the impact on short-term investment security is likely to be limited.

More difficult to manage, and potentially larger in magnitude, is the uncertainty about the avoided fossil fuel consumption. In the case of Thailand, the impact of different avoided cost scenarios in fact dwarfs the uncertainty about renewable energy cost: between the nine main marginal fuel price scenarios, the incremental cost varied between negative USD 22bn and positive USD 30bn – and none of the scenarios seem entirely implausible. This range of cost corresponds to -4.7% and +4.5% of Thailand's GDP in 2012 [59], which compares to the total government tax revenue in 2013 of about 16.5% of GDP [59].

6.2. Policy Implications

The quantitative case study results suggest that the incremental cost of renewable electricity in developing countries is still substantial. Any supported FIT therefore needs to be designed with all major cost drivers in mind in order to minimize necessary financial assistance. The model results suggest that the incremental FIT cost is largely determined by (1) the growth rate of different renewable energy sources, (2) the FIT rates for each technology and (3) the displaced electricity sources. The policy implications of these drivers will be discussed in detail in 6.2.1.

Furthermore, the review of proposals in section 2 highlighted that the proposals differ in how they allocate the uncertainty of the avoided cost. In view of its magnitude, highlighted by the quantitative case study, allocating the uncertainty in incremental cost becomes a major challenge in the design of supported FITs. The implications of this finding for policymakers are discussed in section 6.2.2.

6.2.1. Containing the Incremental FIT Cost

Resources and Capacity Growth Rates

When managing the growth rate of different renewable energy sources, donors and national governments should aim to ensure that the best resources and most appropriate technologies are exploited first. Unlike other policy options such as emission trading or technology-neutral reverse auctions, FITs are not designed to prefer the cheapest technology – on the contrary, their success in bringing down costs of technologies such as PV is based on the fact that they allow for

experimentation, learning and economies of scale in technologies that cannot yet compete with established technologies.

Any supported FIT therefore needs to be accompanied by capacity building activities to enhance the local policymakers' and regulators' understanding of the resource potentials of different renewable energy sources and the cost of state-of-the-art technology. Initiatives such as the IRENA Cost Database and the Global Atlas of renewable resources [53] are very important steps in that direction, as are the numerous initiatives going on in the realm of bilateral development cooperation.

Besides technical aspects, international policy learning and the exchange of legislative experience are needed, too. Some developed countries, notably Germany and Spain, have had problems containing the overall cost of their FIT policies because there were no limit to how much of each renewable technology can be installed at any given time, and tariff rates at times did not reflect the actual cost of renewables. Given that developing countries are less well positioned to shoulder unexpected cost overruns, international collaboration is needed to ensure that supported FITs avoid pitfalls that might jeopardize their long-term political legitimacy.

FIT Rates

To ensure that rates are set appropriately, a supported FIT needs to be administered through a carefully designed application, review and licensing process. If the rates are set by the regulator, they should be subject to regular review and revision. Some emerging economies have successfully linked FIT policies to reverse auctions, a measure that could be used to manage both the FIT rates and the cost of new commitments [81]. The Green Climate Fund has also considered this option [37]. In a supported FIT, reverse auctions could be implemented in a two-staged model, with national designated entities applying for batches of FIT projects at fixed rates to the international fund and investors applying to the designated national entity for the individual projects.

The Cost of Avoided Electricity

The third factor – in which fossil fuel sources are displaced by renewable electricity – is at least as important for the incremental cost as the first two factors discussed above, but often neglected in FIT cost analyses [48]. The case study showed that the avoided costs cover a very significant share of the total FIT cost (USD 67bn of the total 88bn, or 76%). What type of electricity is displaced and how its price is determined therefore affects the cost-effectiveness of a supported FIT and its political

feasibility. As such, a supported FIT design should aim to fulfill two requirements with regard to the avoided cost.

The first requirement is that the *most expensive fossil fuel is displaced first*. In many countries, including Thailand, the decommissioning of power plants is not always based on marginal cost, but a complex outcome of contractual and political arrangements. Which electricity is displaced is therefore not always determined by costs alone. Supported FITs should either be designed ex-ante to only cover the cost gap to the most expensive fossil technology in use or – if the international contribution is determined ex-post, as in some of the proposed mechanisms – require that plant decommissioning is cost-based.⁹¹

The second requirement is that the *full avoided fossil electricity cost* provide the basis for calculating the incremental FIT cost. In the case of small quantities of renewable electricity, the avoided cost equals the marginal cost of electricity, which is roughly equal to the *fuel cost* in the case of most fossil fuel powered electricity. Whenever large quantities of renewable electricity are supported, however, the *capital cost* of avoided new fossil power plants needs to be considered in the avoided cost calculations, too. This is inherently difficult because it is based on counterfactuals – i.e. what would have been built without the renewable installations. Developed countries have some experience with determining capacity credits of renewable installations [e.g., 60] and should assist developing countries in designing mechanisms to account for capital cost in the avoided cost of renewable installations.

6.2.2. Allocating the Uncertainty in the Avoided Cost

The quantitative case study illustrated how the three different types of supported FITs differ in the way they allocate the avoided-cost uncertainty between the national and the international side. It also illustrated that the uncertainty within the avoided cost is so large that it may jeopardize the ability of the FIT to attract private sector investment. The choice between the three types of supported FITs therefore critically affects the ability of a supported FIT to achieve its targets.

⁹¹ One way to approximate the marginal cost would be to link support to projected fossil fuel import prices [17], because these are typically more expensive and should therefore be the first to be replaced. However, how to design such a mechanism for countries with multiple import sources and multiple fossil fuels, such as Thailand, requires further investigation.

If the avoided cost is absorbed by the national government, as under *domestically managed supported FITs*, the policy may become unsustainable domestically, as recent experience in Europe suggests. In the long run, surging incremental costs may delegitimize support for new projects and lead to policy changes, as happened in Germany [61,62]. New investments become less attractive or even unprofitable, potentially compromising long-term diffusion targets. In the short term, political legitimacy may also diminish so far that FIT revenues are changed or taxed retroactively, as with Spain and The Czech Republic, the value of existing renewable generation assets plummets immediately. Both scenarios put the policy's long-term targets at risk. What's more, since the investors' cost of capital is affected by their and the lenders' degree of trust in the ability of the budget-balancing entity to deliver on its promise over the entire life-time of the project, even the *prospect* of either scenario may inhibit the FIT from attaining its targets cost-effectively. In addition, reducing the dependence on volatile fossil fuel prices is a major motivation for developing countries to invest in renewables [63] – requiring the host country to balance this volatile avoided cost would re-introduce the dependence on fuel prices and could therefore remove most incentives to invest in the first place. On the other hand, assigning this uncertainty to the international side, as done by the *globally managed FITs*, renders credible long-term commitments politically difficult, and very large bilateral commitments probably infeasible.

It seems unrealistic that one solution to this conundrum can satisfy all combinations of donor and host countries. For least-developed countries it might be necessary for international donors to absorb the full avoided cost risk by guaranteeing the full FIT payments (as proposed by *globally managed FITs*), whereas *domestically managed supported FITs* could be more appropriate for upper middle-income countries, because they can be expected to shoulder most of the avoided cost risks of the FIT policies. Sharing the uncertainty between the national and international side, as done by *globally managed incremental FITs*, could be a suitable approach for the many developing countries that lie in between the two extremes. For the design of a globally applicable mechanism, differentiating the budget-balancing responsibility depending on the income-level of the recipient country and other characteristics such as the existing fuel mix, thus might be more promising than a one-size-fits all approach.

6.3. Limitations

A techno-economic model such as the one presented here can provide quantitative estimates for the investigated variables, but also has inherent limitations. Thus, three main factors need to be

emphasized. First and foremost, although the model's assumption aimed to reflect the economics of projects in Thailand by using local sources whenever possible, all absolute model results are to be taken with a grain of salt. Investment cost parameters for renewable and fossil generation in particular varied by two-digit percentages between reviewed studies and are thus particularly subject to uncertainty. A second important limitation is that this paper employed sensitivity and scenario analyses because it was impossible to obtain probabilities for different cost parameters or trends. However, the real policy cost uncertainty is a function of *probabilities* in addition to *sensitivities*. Better models to estimate the uncertainty of the policy cost need to be built before any of the proposed mechanisms can be rolled out on a large scale. Thirdly, the model assumed that all FIT payments are made in USD and neglected the currency risk, which could be a significant barrier for developing countries when providing USD tariffs [7]. How the currency risk is treated by different supported FIT proposals and how significant it is compared to other drivers of uncertainty should be the subject of further research.

The presented case study can thus only provide one additional step toward a better understanding of the economics of renewable energy in developing countries and international support mechanisms.

7. Conclusion

This paper investigated how feed-in tariffs (FITs) in developing countries can be supported through direct international financial assistance. FITs in *developed* countries have been successful in attracting private sector investments because of the secure and predictable cash flows they provide. Many developing country governments, international organizations, NGOs and international donors are therefore considering the option of internationally-supported FITs in *developing* countries to decouple their economic growth from greenhouse gas emissions.

However, given the long-term nature of the promised payments, designing internationally supported FIT mechanisms that provide the same level of investment security as in developed countries will be challenging. This article aimed to inform the discussion on how to design such a mechanism. It first reviewed and classified proposed mechanisms, before presenting a techno-economic analysis of a potential internationally supported FIT to assist Thailand's renewable energy targets for 2021.

Four main conclusions can be drawn from the analysis of the proposed mechanisms and the quantitative case study. First, the *magnitude* of the incremental cost of supported FITs is considerable. In the considered case of Thailand, the incremental cost of the FIT were estimated at USD 21bn, or

3.15% of Thailand's GDP in 2012. This magnitude of necessary commitments suggests that a global mechanism to channel financing to FITs in developing countries would have to be established outside the currently existing institutional landscape. The Green Climate Fund under the UNFCCC could be a suitable vehicle if the proposed USD 100bn per year from 2020 will indeed be raised from developed economies, but a long process of demonstration and institutional experimentation will surely be necessary to the build trust required before donors commit such large sums of money over decades.

Second, the incremental costs of supported FITs in developing countries are very *uncertain*. In the presented avoided cost scenarios for the case of Thailand, which all assume the same diffusion of renewable energy at the same *absolute cost* of energy, the *incremental cost* varied between -4.7% and +4.5% of Thailand's GDP in 2012. Because this uncertainty is only resolved over the lifetime of the FIT policy, which includes the lifetime of all supported projects, it implies further challenges for the design and implementation of a supported FIT: Donor countries will be unwilling to commit to financial assistance flows without knowing their eventual volume, while investors will only be attracted with a clear, long-term support commitment. Other options for international support for FITs in developing countries that do not envision the international side to directly cover part of the FIT payments, notably initiatives to reduce investment cost and investment risks [e.g., 23], are not subject to this uncertainty. These options might therefore face fewer political and institutional challenges in the short term.

Third, the uncertainty in the incremental cost is driven, to a large extent, by the uncertain *savings from avoided fossil fuel consumption*. This is in part due to the absolute size of the avoided cost: In the case of Thailand, the incremental cost of the FIT were only 24% of the total FIT cost, because the avoided fossil fuel cost covered the remaining 76%. But it is also due to the nature of the uncertainty. Unlike the cost of the supported renewable electricity, which is also uncertain but can be managed by carefully designing the process in which commitments are made, the avoided cost uncertainty is resolved only over the life-time of the supported projects. Fuel prices may vary substantially over the 10-20 years that FIT payments have to be committed, and changes over time in the type of displaced electricity may result in large step changes in the avoided cost. In addition, the savings from the avoided fossil fuel consumption have to be determined through an analysis of the counterfactuals - i.e., by determining which power plants would have been built and which types of fuels consumed without the renewable installations. Arriving at a process to determine these counterfactuals that satisfies domestic governments and international donors will require much experimentation and policy learning.

Fourth, the reviewed proposals for internationally supported FITs differ in how they allocate the avoided cost uncertainty between national governments and international donors. Some proposals assign all cost uncertainty to the national government, whereas the international side assumes all uncertainty in others. Ideally, the avoided cost uncertainty would be allocated dependent on characteristics of the host country. While emerging middle-income countries can be expected to absorb this risk, international donors might be willing assume it when they support the least-developed countries. A support mechanism that differentiates the tariff payment structure depending on characteristics of the recipient country could thus be more suitable for large-scale support than a one-size-fits all approach.

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Appendix

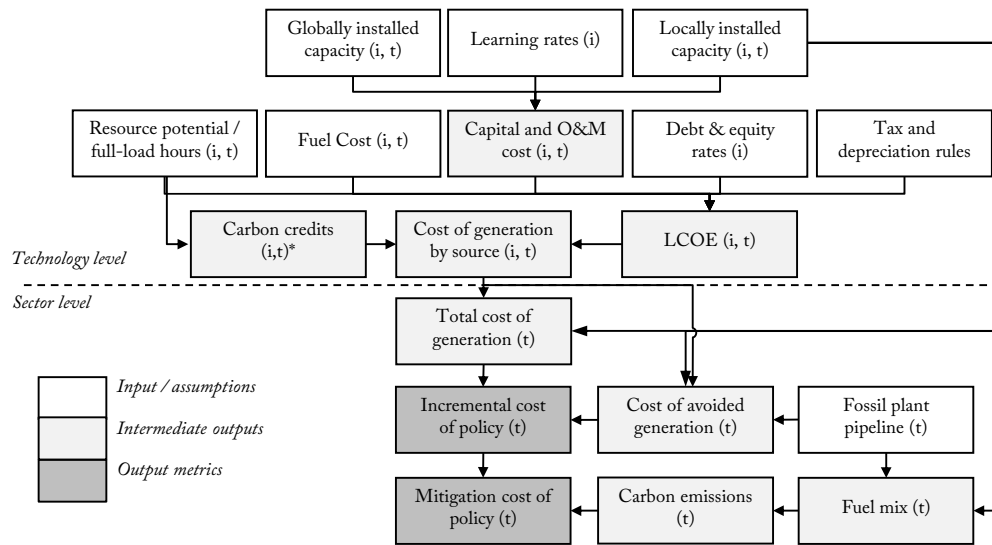


Figure 9: Model structure: Key relationships between input and output variables (function of technology i , year t) in the techno-economic model

Table 4: Input assumptions for renewable energy technologies (values for 2012; in USD₂₀₁₂)

	Size (MW)	Lifetime [a]	Investment ^d [USD/kW]	Learning rate	O&M fix [USD/kW _a]	O&M variable [USD/MWh]	Fuel cost [USD/MWh]	Efficiency [%]	Capacity factor [%]	Dependable capacity [%]
Wind	10	20	1,980 ^a	4.3 ⁱ	60 ^a	0 ^a	-	-	31.8 ^c	9 ^e
PV	10	20	2,830 ^a	20 ^j	50 ^a	0 ^a	-	-	19.8 ^c	20 ^f
CSP	5	20	4,910 ^a	14.6 ^j	50 ^a	0 ^a	-	-	21.5 ^c	70 ^g
Biomass	10	20	2,157 ^b	5 ^k	0 ^b	10.4 ^b	41.2 ^b	19.8% ^b	69 ^b	55 ^h
Biogas	1	20	2,554 ^c	5 ^k	116 ^c	0 ^c	10 ^c	31% ^c	70 ^c	21 ^h
Hydro	1	20	2,800 ^d	5 ^k	112 ^d	0 ^d	-	-	29 ⁱ	40 ^h

^aNREL [65]; ^bDelivand et al. [50]; ^cPattanaopongchai and Limmeechokchai (2011); ^dIRENA [67]; ^ecalculated based on data from IRENA [53]; ^fNakrisuk and Audomvongseree [68]; ^gSangarasri-Greacen and Greacen [56]; ^hMunchareon et al. [69]; ⁱPromjiraprawat and Limmeechokchai [52]; ^jHayward & Graham [70]; ^kMott McDonald [71]; ^lThe initial investment cost and the fixed O&M cost of each technology were assumed to decrease over time as a function of global cumulative installations and a fixed learning rate [72]. Global installation trends and values for 2011 were taken from IEA [73]; starting values for biomass and biogas from IRENA [74]; starting values for micro hydro from IRENA [75].

Table 5: Input assumptions for dispatchable fossil fuel technologies (values for 2012; in USD₂₀₁₂)

	Lifetime [a]	Investment ^e [USD/kW]	O&M fixed [USD/ kW _a]	O&M variable [USD/ MWh]	Fuel efficiency [%]	Fuel cost ^b [cUSD/ kW _{h,a}]	Capacity factor [%]	Carbon emissions [tCO ₂ / MWh]
Subcritic. lignite	30	1,125 ^a	38.91 ^b	11.02 ^b	35 ^b	0.54 ^d	90	1,159 ^b
IGCC lignite	30	2,830 ^c	50 ^c	7.9 ^c	46 ^c	0.54 ^d	90	882
Adv. nuclear	40	5,429 ^e	91.65 ^c	2.1 ^c	33 ^c	0.31 ^d	90	21 ^b
Gas turbine	n/a	n/a	7.21 ^c	15.28 ^c	31.4 ^c	2.49 ^e	30	631 ^b
CCGT	30	1,006 ^c	15.1 ^c	3.21 ^c	54 ^c	2.49 ^e	60	404 ^b
Subcritic. coal	n/a	n/a	38 ^b	0.04 ^b	36 ^b	1.39 ^f	90	973 ^b
Supercrit. coal	30	2,934 ^e	31.18 ^d	4.7 ^d	39 ^c	1.39 ^f	90	782 ^b
IGCC coal	30	3,784 ^e	51.39 ^c	8.45 ^c	39 ^c	1.39 ^f	90	782 ^b
Diesel turbine	n/a	n/a	12 ^a	28.6 ^a	22 ^a	6.81 ^d	30	808 ^b

CCGT: combined cycle gas turbine; IGCC: integrated gasification combined cycle; ^aPattanapongchai and Limmeechokchai [66]; ^bPromjiraprawat and Limmeechokchai [52]; ^cDOE/EIA [76]; ^dEPP0 [77]; ^eprice for natural gas is for imports from Myanmar, from PTIT [78] ^fIEA [2]; ^gInvestment cost and fixed O&M are assumed to decrease by 2.0% p.a.; ^hFuel price reflect average natural gas prices, see section 4.3; n/a: Not needed because no new power plants in the pipeline

Table 6: Different pathways for natural gas prices 2010-2050 in Thailand. Starting values are taken from PTIT [78]; trend scenarios are adopted and extrapolated from IEA [57], and applied to the starting values.

Starting price	Trend scenario	2010	2015	2020	2025	2030	2035	2040	2045	2050
LNG import price	450 degree	6.95	7.52	7.58	7.58	7.64	7.64	7.64	7.64	7.64
	New policies	6.95	7.71	8.15	8.47	8.78	9.03	9.29	9.54	9.79
	Current policies	6.95	8.02	8.53	8.97	9.35	9.60	9.86	10.11	10.36
Average import price	450 degree	8.38	9.06	9.14	9.14	9.22	9.22	9.22	9.22	9.22
	New policies	8.38	9.29	9.83	10.21	10.59	10.89	11.20	11.50	11.81
	Current policies	8.38	9.67	10.28	10.82	11.27	11.58	11.88	12.19	12.49
Average price	450 degree	14.61	15.81	15.94	15.94	16.08	16.08	16.08	16.08	16.08
	New policies	14.61	16.21	17.14	17.80	18.47	19.00	19.53	20.06	20.59
	Current policies	14.61	16.87	17.94	18.87	19.66	20.19	20.73	21.26	21.79

Table 7: Sector-wide assumptions in the model

Factor	Assumption	Source
Currency	USD 2012 in real terms	---
Exchange rate	1 USD = 31.5 Thai Baht	The World Bank
Inflation	2.5%	Bank of Thailand
Equity/debt split	30/70	Current practice
Return on equity	11.2% real	UNFCCC [79]
Lending rate	6.7% nominal	Ondraczek et al. [80]
Loan tenor	Half of investment lifetime	Waissbein et al. [23]
Tax rate	30%	Current practice
Depreciation	Linear, max 5% p.a., min book value 5%	Current practice
Discounting of public expenditures	Equals 40-year bond yield of 4.43 %	Thai Bond Market Association ^a

^a<http://www.thaibma.or.th/yieldcurve/YieldTtm.aspx>; assessed on 4/3/2014

Japan's Post-Fukushima Challenge - Implications From the German Experience on Renewable Energy Policy[^]

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Abstract

The Japanese electricity sector is facing serious challenges in the aftermath of the Fukushima nuclear disaster. The government has responded to the crisis with a new feed-in-tariff to promote increased utilization of renewable energy, and proposed to reduce the dependence on nuclear power. In this paper, we liken the transition implied by recently updated goals for the diffusion of renewables in Japan 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 focus on the new Japanese feed-in tariff for solar photovoltaics. In view of the recent developments in Germany, we emphasize the importance of the scheme's political legitimacy, which needs to be maintained through adequate design of both policy instrument and political process. We conclude with policy implications and a targeted research agenda.

Keywords: Renewable energy policy, Nuclear energy, Solar photovoltaics, Feed-in-tariff, Japan, Germany

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 and a nuclear meltdown at the Fukushima Dai-ichi power plant. The accident and the continued struggle to contain radiation at the 4.7 GW nuclear facilities have plunged the country's electricity sector into a massive crisis. Having revealed the vulnerability of the country's power system, the disaster appears set to shift the fundamental paradigms of Japan's energy policy.

Before Fukushima, the country's long-term energy strategy had revolved around an ever-increasing share of nuclear power. Japan's energy strategy is formulated in the 'Basic Energy Plan', outlining the long-term strategy for the country's future energy mix. The latest version in 2010 targeted the nuclear share of power production to surge from roughly 30% to 50% by 2030 (see Duffield and Woodall, 2011). This strategy has been shaken to its very foundations. A substantial part of Japan's nuclear capacity has been forced to shut down in the aftermath of the earthquake.⁹² The decision over whether idle reactors should be allowed to restart has been delegated to the local governments of jurisdiction (IEEJ, 2011a). This currently represents a significant challenge, amid a public growing increasingly distrustful of nuclear power (DeWit, 2011a).

Consequently, Japan declared in an energy white paper in October 2011 that it would aim to reduce the dependency on nuclear power and revise the Basic Energy Plan, starting "from a blank state" (METI, 2011a, p. 2). The Fukushima meltdown thus represents a major turning point and a huge opportunity for Japan's energy future. The government's response will set the course regarding nuclear safety, energy security, costs, and carbon emissions. Whether and how these objectives can be reconciled will depend on the political steps taken in the in the coming years (Ashina et al., 2011). It has been proposed that Japan should follow the example of countries that successfully promoted the use of renewable energy, such as Germany (e.g., DeWit and Kaneko, 2011; Iida, 2011). In this paper, we liken the transition implied by recently proposed goals for renewables to the transition Germany underwent in the last decade. In particular, we describe some important lessons learned from the

⁹² In addition to the units immediately affected, the government ordered all reactors that have since been shut down for regular inspections to remain offline for 'stress tests'. In total, 51 out of 54 nuclear reactors were out of service in early 2012 (JAIF, 2012).

support of solar photovoltaics (PV) in Germany and discuss their implications in the context of Japanese policy.

2. Renewable Energy Policy in Japan Before Fukushima

Lacking significant domestic fossil fuel resources, Japanese energy policy has always been centered around concerns of energy security (Bobrow and Kudrle, 1987; Toichi, 2003). More recently, pledges to cut carbon emissions by 25% by 2020 from 1990 levels, and by roughly 80% by 2050 (Tollefson, 2011), have added reduced carbon intensity to the country's long-term goals. In this context, the Japanese energy strategy before Fukushima increasingly focused on nuclear power as a (nominally) cheap, quasi-indigenous, and low carbon power source.

In contrast, renewables played a rather minor role before Fukushima. Despite policy support in the form of investment subsidies (since the mid-1990s) and a Renewable Portfolio Standard (since 2003), PV and wind power accounted for only 0.21% and 0.24% of electricity production in 2008 (IEA, 2011). Some geothermal projects were installed in the 1970s and 1990s (533 MW in total), but growth has slowed to nil since 1999 (Sugino and Akeno, 2010). When it became apparent that the renewable energy goals for 2010 would not be met (the goal was 1.35% of electricity production), a feed-in tariff (FIT) was eventually introduced in Japan in 2009.⁹³ However, the scheme had been restricted to residential PV systems, and rewarded only net electricity production of the households (IEA, 2010).

Taken together, we see that no stringent regulatory framework encouraging significant investment in renewables had been implemented before Fukushima (Maruyama et al., 2007; DeWit and Iida, 2011; Moe, 2012). Maruyama et al. (2007, p. 2763) even come to the rather sobering conclusion that "Japan's renewable energy policy [was] impeding renewable energy use rather than contributing to the spread of it". The main reason is to be found in the regulatory structure. Most responsibilities related to the energy sector are concentrated in the Ministry of Economy, Trade, and Industry (METI), including the Agency for Natural Resources and Energy responsible for renewables. The METI is by tradition 'in league' with powerful industry organizations, such as Denjiren (the Federation of Electric

⁹³ A feed-in tariff guarantees the power producer a fixed electricity purchase tariff for a specified period (often 10-20 years), typically in combination with preferential grid access for the electricity produced.

Power Companies of Japan), and Keidanren (the Japanese Business Federation). Through this ‘cozy relationship’ between monopolistic utilities, industry, and a pro-nuclear bureaucracy (Aldrich, 2011, p. 62; also DeWit and Kaneko, 2011), vested interests have been able to hollow out all attempts towards stringent policies for renewables (DeWit and Iida, 2011, Moe, 2012).⁹⁴

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

In the immediate aftermath of the disaster, the Japanese energy sector administration faced an imminent supply shortage. For historical reasons, the grid is running on different frequencies. Therefore, being practically unable to import electricity from Western to Eastern Japan, where the disaster hit, utilities concentrated their efforts on curbing peak demand, managing rolling blackouts, and reactivating ‘mothballed’ (retired but not decommissioned) thermal power plants (IEEJ, 2011a, 2011b).

In the medium term, in view of the immediate supply shortage, experts foresee an increasing share of power production from fossil fuels, especially natural gas (ACCJ, 2011; Tollefson, 2011). In the long term however, the Fukushima disaster has highlighted the merits of a decentralized and resilient energy supply system. Then premier Naoto Kan had outlined in June 2011 a plan to increase the contribution of renewables to power supply to 20% by 2020, a share that even the most ambitious plans did not envisage before 2030. To that end, he proposed to revise the existing FIT and to extend it to other forms of renewable electricity, and offered his resignation conditional on, inter alia, the Diet passing it (Muramatsu et al., 2011). Amid the rising concerns about nuclear energy, a coalition of public figures, companies, politicians, and NPOs formed in support of the new bill (DeWit, 2011a). Eventually, on August 26, 2011 the extended FIT was passed by the Diet (the “Act on Purchase of Renewable Energy Sourced Electricity by Electric Utilities”, METI, 2011b). The new FIT starts in July, 2012, encompassing PV, wind power, small hydro, geothermal and biomass (Ayoub and Yuji, 2012).

This creates a regulatory situation similar to that under the German Renewable Energy Act (Langniß et al., 2009). Indeed, the 20%-target formulated by former Premier Naoto Kan implies an electricity

⁹⁴ Among the influential opponents of renewable energy were the fishing industry, opposing offshore renewables, and the Onsen (bathing) industry, opposing the exploitation of geothermal energy.

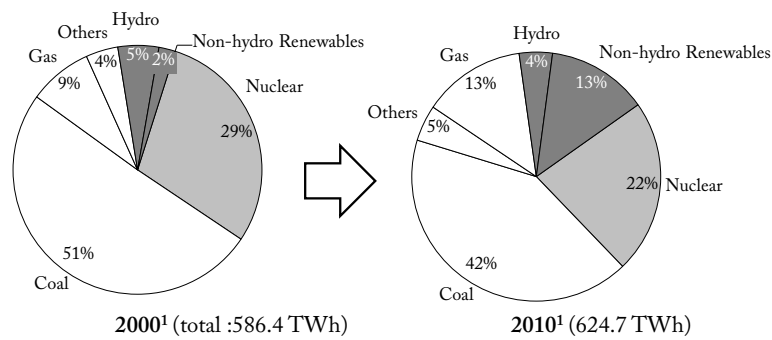
sector transformation similar to the one that took place in Germany in the last decade (see Figure 1). Germany produced 7% of its electricity from renewables including hydropower and 29% from nuclear in 2000; the numbers for Japan were 8% and 30% in 2009. In the decade after 2000, Germany installed some 43 GW of renewables and increased their share to 17% of electricity production. Japan aims to raise the renewable share of power generation from 8% to 20% in the next 9 years (requiring roughly 70 GW of capacity, see Duffield and Woodall, 2011).⁹⁵

Having long been a 'pet project' (DeWit, 2009) of the METI, PV seems perfectly positioned to play a major role in the proposed transition. Not only because PV plants are quick to install, but also because they are suitable to fill the current gap between electric capacity and peak demand around noon. In June 2011, the government announced a goal of putting PV systems on 10 million roofs by 2030. Also, the revised FIT envisages PV to account for more than 80% of newly installed capacity in the coming decade (METI, 2011c). Japanese industrial expertise in solar energy is significant, and also among the political proponents of renewable energy, solar energy enjoys a special position (see, e.g., calls for a 'solar belt' in East Japan, Son and DeWit, 2011). Therefore, it appears appropriate to outline some of the lessons learned from the policies for PV in Germany.

⁹⁵ As Figure 1 shows, even with 20% renewables a supply gap of about 20% remains, if no new nuclear power plants are to be build and old plants retire after 40 years of operation, as the government recently announced (Kageyama, 2012). This illustrates the urgency of the Japanese energy crisis.

Transformation of the electricity sector in Germany in the past decade

Electricity production by source



Projected transformation in Japan

Electricity production by source

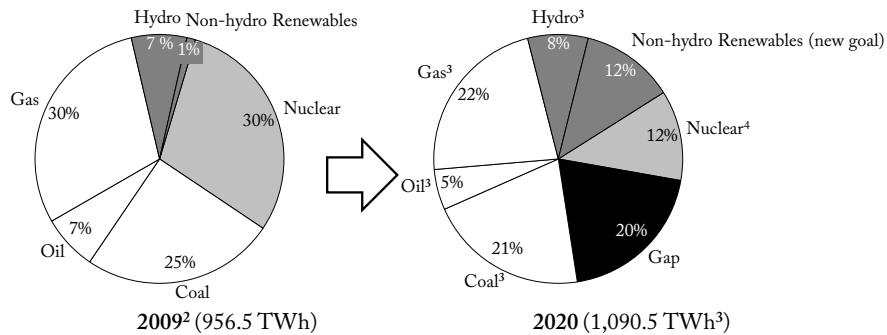


Figure 1: Comparison of German energy sector transformation 2000-2010 with challenges faced by Japan in period 2009-2019; ¹data from BMWi (2011); ²data from FEPJ (2011); ³data from projection for 2019 by FEPJ (2011); ⁴data for nuclear power from projection by Iida (2011); non-hydro renewable contribution in 2020 assumed to fulfill 20% goal announced in June, 2011. To avoid double counting, we excluded pumped hydropower, assuming the split of conventional/pumped hydropower to remain constant at the level of 2005 given in IEA (2008).

4. Lessons from the PV FIT in Germany applied to the Japanese Context

Although a widely appraised success story, the politics behind the German renewable energy policy are all but smooth. The German FIT, or ‘Renewable Energy Act’, came into effect in 2000, guaranteeing (differentiated) purchase tariffs for wind, PV, small hydropower, geothermal, biomass, as well as landfill, sewage, and mine gas (BMU, 2011a). Initially designed to be updated every four years, the German FIT has been amended and revised repeatedly. The design of the law itself is subject to a continuous learning and adaptation process. In the following, we will outline what we believe are the three main political challenges in this process: mounting costs, low R&D intensity (R&D per sales), and rising net imports. All three illustrate the dynamics of conflicting policy objectives.

The political responsibility for the PV FIT is held jointly by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the Federal Ministry of Economics and

Technology (BMWi). The BMU leads the drafting process, while the BMWi contributes to the law's bi-annual evaluation. According to the official objectives, the FIT aims to integrate environmental policy (ensure a sustainable energy supply and conserve fossil resources), economic policy (contain the overall costs, including external effects, of energy supply in the long term), and technology policy (foster technical change in renewable energy technologies). Industrial policy objectives are not explicitly mentioned, but the competitiveness of the domestic renewable energy industry (in terms of jobs, exports, etc.) features prominently among both proponents and critics of the FIT. For instance, the current Minister of the Environment declared that he objects to fundamental changes to the FIT because he wants "the [German] solar industry to survive" (Photon, 2012).

With regard to its main purpose, attracting private investment, the German FIT was successful. As for PV, the installed capacity surged from 32 MW in 1999 to 17,320 MW in 2010, making Germany by far the world's largest market for solar cells. Critics argue that the FIT has even been too effective. Before a limit to annual installations was removed in 2004, household investments in rooftop systems, which contributed significantly to the diffusion of PV and the scheme's legitimacy in the general public, did not take off. But without the 'cap', the volatile domestic market and the overall cost burden proved extremely difficult to contain. Over the last couple of years, the mounting payment commitments of the scheme have fuelled a public and scientific debate about the scheme's future (Frondelet al., 2009). PV accounted for only about 14% of electricity production from non-hydro renewables in 2010 (BMU, 2011). At the same time, cumulative committed payments (discounted, over 20 years) reached approximately €100bn in 2011 (Frondelet, 2012), with annual payments accounting for more than 40% of the total payments under the EEG (BMU, 2011b).

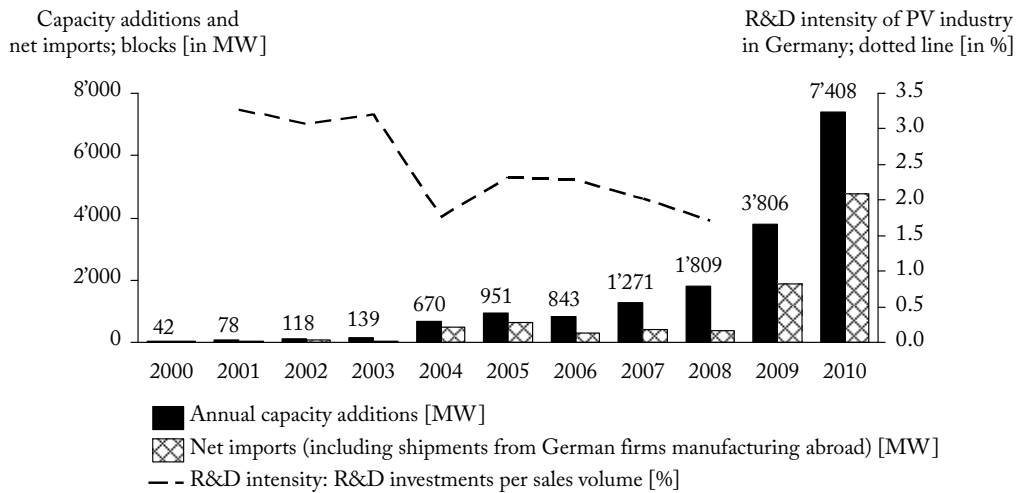


Figure 2: Main challenges for legitimacy of FIT for PV in Germany: installations and net imports are growing exponentially while the research intensity in the industry is declining. Data from the German industry association BSW-Solar (2010, 2011, 2012), which since 2011 refrains from publishing R&D data; net imports for 2009 and 2010 calculated from Photon (2011).

Besides the overall costs, issues in terms of technology policy and industrial policy objectives have further undermined the scheme's legitimacy. On the one hand, recent research suggests that the generous FIT incentivized firms to reallocate resources to new production capacity and, in relative terms, away from R&D (Hoppmann et al., 2011). This led to a declining R&D quota (see Figure 2) that even the industry itself considers unsustainable (Prognos and Roland Berger, 2010). On the other hand, since 2010 the imports of PV modules far outweigh exports (displayed in Figure 2), and German manufacturers increasingly move their production to low-wage countries. Both developments attracted much criticism in the media, although not always justified. Total R&D expenditures in the industry grew 17-fold from 2001 to 2008, but when net imports surged and firms moved production to Asia, the declining R&D intensity of firms that were 'busy growing' was an easy target for the media. The FIT was termed a 'failed' industry and technology policy (Schroer, 2010; Wetzels, 2011), and critics raised concerns about the long-term perspectives of PV technology and its costs. This criticism is unlikely to harm the overall prospects of renewables in Germany, given the decision to phase-out nuclear power in Germany by 2022 (as a consequence of the Fukushima accident). However, the legitimacy of support for PV is eroding, resulting in, e.g., recent high-level calls to end the FIT and replace it with other, less generous policies (Sigmund et al., 2012).

These recent experiences in Germany are particularly relevant for the Japanese context, considering the idiosyncrasies of Japanese politics and the current developments in the PV industry. In Germany, the balance of powers between BMU and BMWi has created a policy environment that provided for intermediation between different objectives during the initial implementation of the FIT. While the

BMU is a strong proponent of renewables, mainly for environmental reasons, the BMWi aims at conformity with economic and industry political targets. This makes it difficult for vested interests from either side of the debate to erode the policy. In Japan, by contrast, the concentration of regulatory authority in the METI assigns a prominent role to economic policy objectives. This makes stringent incentives to invest in renewables very difficult to implement. The new FIT is a major step ahead of the intransparent RPS. But even in this legislation, interests of the big energy monopolies are apparent: Electric utilities can refuse to purchase the power from renewables if it is “likely to be a hindrance to securing the smooth supply of electricity” (METI, 2011d). Preventing unwilling utilities from exploiting this loophole will be extremely difficult. Surely, the clout of the nuclear industry in the energy policy process has been reduced by the Fukushima disaster (DeWit, 2011a; Kingston, 2011). But even if such opposition is to wane in face of new political realities, it is very likely that paying attention to economic objectives will significantly ease the political process in the revisions (planned to occur at least every three years).

In the past, whenever plans for the Japanese energy sector and the diffusion of renewables have been drafted, they prominently featured industrial policy objectives. The new FIT, too, lists “promotion of the domestic industry, and thereby strengthening the international competitiveness of [Japan]” as one of its main targets. At the same time, changes in the global industry landscape might make it difficult for Japan to achieve such objectives. Early market support and research funding in Japan in the 1980s and 90s had spurred 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. These cost advantage of Chinese/Taiwanese firms will surely pose a significant challenge for their Japanese counterparts.⁹⁶

Japan is still a net exporter of PV cells, and domestic firms may regain momentum from the new FIT. Furthermore, the incremental costs of installed capacity under the FIT will be lower than in Germany,

⁹⁶ Since the relationship between Japan and China is still a sensitive issue, a FIT that obliges electricity customers to pay a premium for the import of Chinese solar cells could be expected to spur even more opposition in Japan than it did in Germany.

due to rapid reduction in price of solar cells in the last 2 years and Japan's relatively high electricity prices. But the future of the Japanese energy sector is contested (DeWit, 2011b), and the PV industry has become much more competitive than it was a decade ago.

5. Implications for Japanese Energy Policy and a Research Agenda

In this viewpoint, we have argued that the allocation of political responsibilities to the METI renders economic and industrial policy aspects of the FIT particularly important. In the meantime, at least for PV, changes in the global industry might make these objectives especially difficult to fulfill. Therefore, the government will have to work towards reducing the impact of industry interests on the regulatory process if any policy for renewables is to be effective (Kanie, 2011a, 2011b). A process of 'policy learning' and refinement, as achieved in Germany over the last 10 years, is only possible under a political framework with balanced powers and objectives.

In the short run, closing the new FIT's grid stability loophole must be the first priority – it was not before unlimited grid access was granted to renewables in Germany that significant investment was attracted. Further, institutionalizing an FIT revision process which involves several ministries, such as for the German FIT, could enhance transparency of the political process. In the long run, the government should strive for an integrative policy framework, balancing priorities of energy security, environmental policy, climate policy, as well as economic and industrial policy. To that end, responsibilities for energy policy could be shared between the METI and the Ministry of the Environment, or allocated to a new ministry for the environment and energy (Kanie, 2011a). The ongoing initiative made by the National Policy Unit of the Cabinet Secretariat to discuss energy policy in connection with environmental issues at the Energy and Environment Council, which was established on 22 June 2011, can serve as a point of departure. This council is not sufficient, however, because it is not yet institutionalized and could be terminated easily.

In the meantime, Japan will have to find ways to reconcile the different objectives under the current framework. In particular, it should aim at fostering both rapid cost reductions and industrial competitiveness. Here, Japan's challenge is representative of that of many developed and developing countries in search of integrative energy policies that bring both economic and environmental benefits (Bazilian et al., 2010). To inform such policy decisions, we need to better understand the impact that policies stimulating investment in new technology, such as a FIT or investment subsidies, have on technical change and industrial performance. Theory and evidence suggest that demand-pull policies

not only speed up diffusion, but also 'induce' innovation (Jaffe et al., 2002). Industrial performance is suggested to improve by the Porter Hypothesis (Porter and van der Linde, 1995) and the literature on 'lead markets' (Beise-Zee, 2004), as firms may receive a competitive advantage when there is strict regulation in the home market. However, cases such wind in Californian in the 1980s (see Nemet, 2009) and the PV FIT in Germany show that there are important context and technology-specific factors that may lead to adverse outcomes. An improved understanding of these context effects is indispensable to reliably foresee policy implications.

From an industrial policy perspective, the focus on market subsidies rather than research funding in Germany appears to have created incentives to favor deadweight effects over long-term research. One way to avoid such situation could be for Japan to tap into its own environmental policy experience. Indeed, for a product very similar to PV modules, liquid crystalline displays, Japan has, with the 'Top-Runner' program, implemented one of the world's most successful environmental policies. Enacted in 1998 by the METI, the scheme is designed to stimulate energy efficiency for household and office appliances. It does so by iteratively setting mandatory efficiency standards based on the most efficient products on the market, and consultations with advisory committees (Kimura, 2010).

Integrating aspects from the successful 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. A modified FIT could, for instance, require solar modules to fulfill a condition similar to one that had been implemented in an investment subsidy that was granted to residential systems in 2009: in order to receive the subsidy, conversion efficiency had to exceed the average on the market (IEA, 2010). Since Japan has a well-functioning innovation system in the semiconductor and solar PV industries, and is a high-wage country, we expect that such a policy is much better suited to the capabilities of the industry than a scheme merely rewarding production at the lowest costs. How to implement such a policy, how to reconcile it with WTO rules, and how to design a committee-based standard-setting process, requires further research. In practice, a bigger challenge may exist in bridging bureaucratic boundaries and creating a well-coordinated policy mix. Yet a successful integration of economic and environmental benefits might turn problem-fraught Japan into a role model for renewable energy policy.

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