GRETCHEN
policy mix for renewables

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Green change: renewable energies, policy mix and innovation

Results of the GRETCHEN project concerning the influence of the policy mix on technological and structural change in renewable power generation technologies in Germany

Fraunhofer ISI

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Contents

Executive Summary

GRETCHEN – The impact of the German policy mix for REnewables on Technological and structural CHange in renewable power gENeration technologies

A far-reaching transformation to green, CO_2–free solutions is needed to achieve the ambitious climate policy target of limiting the global temperature rise to not more than 2°C. With this in mind, the GRETCHEN project explored the impacts of the policy mix on innovation in renewable power generation technologies in Germany at three levels:

- the micro level, focusing on the perspective of individual companies,
- the meso level, examining industry structures and the innovation system, and
- the macro level, modelling macroeconomic effects and CO_2 emissions.

The impact of the policy mix was analysed at these three levels for the following aspects:

- political targets to expand power generation from renewable energy sources,
- technology push, demand pull and systemic instruments as well as their interaction within the instrument mix, and
- the consistency and credibility of the policy mix and the coherence of political processes.

The policy mix needed for a green transformation of the energy system can be considered holistically and evaluated with regard to its innovation impact based on the policy mix concept developed in the GRETCHEN project.

Market and technology development of renewable power generation technologies

Transforming the energy system into sustainable power generation requires the development of new technologies and the improvement of existing ones. The GRETCHEN analyses show that renewable power generation technologies have been subject to rapid technological change over the last few decades:

- the number of scientific publications related to photovoltaics has risen sharply over time in Germany,
- patent applications in photovoltaics and wind power have developed above the general patenting trend in Germany,
- cooperation between various actors in the innovation systems for photovoltaics and wind power has increased greatly and supports innovation activities through the resulting intensive knowledge exchange,
- technology costs have fallen substantially, so that several renewable power generation technologies are now competitive with fossil fuel-based technologies,
- the technological competitiveness of Germany in the field of photovoltaics increased noticeably until 2011,
- German manufacturers of renewable power generation technologies have been able to open new export markets with a positive effect on the economy, e.g. in the form of additional jobs, and
- progress has been made in the decarbonisation of the energy system in Germany, and also in other parts of the world via technology transfer.

In spite of these positive trends, the development in Germany has currently slowed down, with some areas more affected than others. However, when viewed globally, the trend towards renewable power generation technologies remains strongly positive.

The policy mix for renewable power generation technologies

Since the German Renewable Energy Sources Act (EEG) was introduced in 2000, the dynamic growth of renewable energies has resulted in increasingly ambitious targets that now foresee an 80 percent share of renewables in Germany's gross electricity consumption in 2050. To meet these political deployment targets, a wide variety of demand pull (e.g. EEG), technology push (e.g. energy research programme), and systemic instruments (e.g. collaborative research) have been introduced over the past decades. Despite this relatively comprehensive mix of instruments, according to the GRETCHEN survey, there has been a clear decrease in the credibility of the policy mix over the last few years with regard to the promotion of power generation from renewable energies. Among other reasons, this is probably due to the controversial political debate about the future of renewable energy support. Moreover, the manufacturers of renewable power generation technologies have a low regard of the coherence of these political decision-making and implementation processes.

The impact of targets and their consistency on innovation

According to the GRETCHEN survey, the expansion targets are one of the most important political drivers of innovation activities among manufacturers of renewable power generation technologies located in Germany. Looking at the case of offshore wind power, it becomes clear the offshore wind strategy, which was technology-specific, stable and consistent over a ten-year period and featured medium and long-term targets, had a significant influence on on companies' innovation activities. Overall, the conducted analyses confirm that decarbonising power generation makes an important contribution to achieving the German government's ambitious climate targets, although these require all other sectors to make significant contributions as well.

The impacts of individual instruments on innovation ...

Technology push, systemic and demand pull instruments each have a significant influence on technological change in the examined technologies.

Technology push instruments have a positive effect on innovation. For instance, they:

- increase the number of patent applications in photovoltaics and wind power,
- raise the R&D expenditure of the manufacturers of renewable power generation technologies,
- increase the size and interconnectedness of networks in the national innovation system for photovoltaics and wind power, and
- facilitate access to international knowledge flows in photovoltaics.

Systemic instruments encourage the development of the innovation system. In particular:

- they promote knowledge exchange among innovators in photovoltaics and wind power, and
- increase international networking in photovoltaics research.

Demand pull instruments not only lay the foundation for the formation of an attractive market, but also have a positive effect on innovation. They lead to:

- a rising number of patent applications in photovoltaics and wind power,
- an increase in innovation activities and R&D expenditure among manufacturers of renewable power generation technologies,
- growth in terms of the size and interconnectedness of networks in the national innovation system for photovoltaics and wind power,
- improved access to international knowledge flows in photovoltaics, and
- increasing technological competitiveness in photovoltaics.

These positive effects on innovation emanating from demand pull instruments trigger a self-reinforcing process of cost reductions and investment in renewable energies that helps to overcome current path dependencies in the energy system. This development does not occur in isolation in Germany, but is enhanced by growing international renewable energy expansion. These global interdependencies have to be taken into account when estimating the effect of the German policy mix.

... and their interaction in the instrument mix

Looking at the mix of instruments reveals that the different instruments mutually reinforce each other's positive impact on innovation. The GRETCHEN analyses indicate that demand pull measures play a key role in the instrument mix. Altogether, a carefully coordinated combination of demand pull, technology push, and systemic instruments is clearly driving innovation. The GRETCHEN survey also shows that a consistent instrument mix helps to increase private spending on R&D. In addition, synergies appear when policy instruments and targets interact. For instance, the expansion targets for renewable energies strengthen the positive effect of technology push instruments on the technological competitiveness in photovoltaics.

Impact of the consistency, credibility and coherence of the policy mix on innovation

Besides ambitious expansion targets and a consistent mix of instruments, it is especially important that the various instruments are also all geared towards the objectives of the *Energiewende* to incentivise innovation activities. The GRETCHEN survey showed that companies spend more on innovation if the mix of instruments appears sufficiently ambitious to actually achieve these objectives. The results also underline that a credible political commitment to the *Energiewende* is an essential factor for businesses' innovation expenditure. On the other hand, the companies' high degree of dissatisfaction with political decision-making processes does not seem to significantly affect their innovation activities.

Impact of the overall policy mix on innovation

The dynamics and diversity of the policy mix and its impact on technological and structural change were examined mainly in individual analyses; merging these analyses contributes to a better understanding of the effect of the overall policy mix on innovation. In addition, a technology-specific, aggregated indicator of the attractiveness of the policy mix was developed within GRETCHEN. This policy mix indicator provides first insights into the overall development of the political framework conditions and their influence on technological change and reveals that the annual patent applications for wind power run almost parallel to the measured attractiveness of the policy mix. For photovoltaics, the GRETCHEN policy mix indicator has fallen rapidly since 2010, accompanied by a considerable slow-down in the patent applications by German inventors.

Policy recommendations

The currently worsening innovation climate for renewable energies is a warning to policy makers. Technological change has been steered in the right direction and now has to be encouraged rather than decelerated, given its many benefits and the ambitious energy and climate targets. Three main policy recommendations can be derived from the GRETCHEN analyses:

- To successfully steer technological change in the energy system, it is essential to have a carefully coordinated combination of different policy instruments. The **policy mix** has to be understood and designed **as a whole** – backing only one instrument will not achieve the desired result.

- In order to stimulate dynamic innovative activity, this policy mix has to be **credible** and internally **consistent** to the greatest possible extent. Without a strong political will for green change, there is uncertainty about future market developments which hinders long-term investments in innovation and threatens Germany's technological competitiveness in the analysed technologies.

- The shift towards renewable power generation technologies is an increasingly global process that will need much **greater supranational coordination** of the policy mix in the future. The discussion about the *Energiewende* in Germany should be specifically orientated towards its **benefits** – in the form of export opportunities, jobs and its contribution to international climate protection and sustainable development, among other things.

Future research requirements

The empirical studies conducted as part of GRETCHEN have led to comprehensive new insights into the effect of the policy mix and revealed where further research is necessary in the fields of the economics of climate change, the economic evaluation of the *Energiewende*, and environmental innovations. Firstly, an improved database is essential for further research, so that the priority must be to close any gaps in the national and international data (especially longer time series, company-level data). Secondly, the impact analysis of the policy mix should be extended to other countries and sectors by combining and further developing quantitative and qualitative research methods.

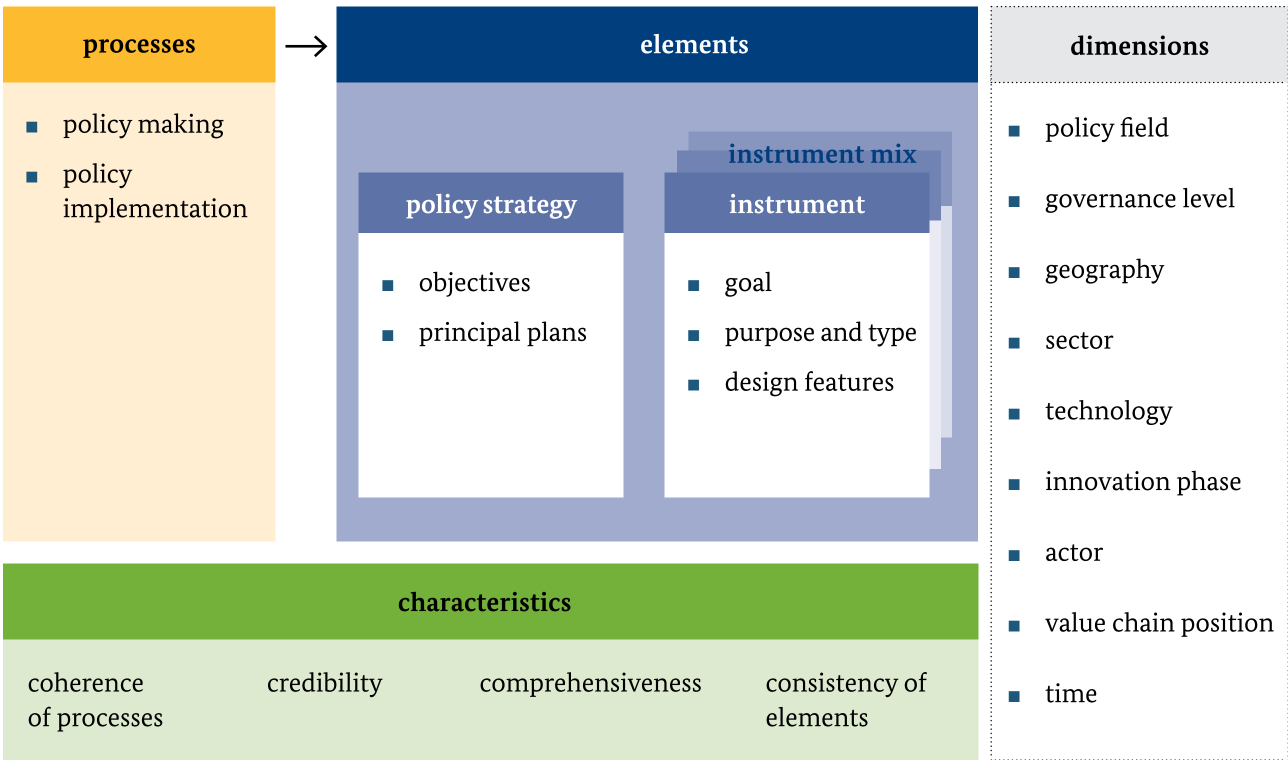
1 Introduction

The energy sector plays a significant role in reaching the ambitious climate policy target of limiting the global temperature increase to 2°C. To this end, technological change has to be redirected and accelerated in the direction of zero-carbon solutions. Because of various market and system failures and the inertia of the existing energy system, it is necessary to use a combination of different policy instruments – a policy mix – to achieve this, which is able to accelerating the decarbonisation of the system. Instruments are needed that promote the research, development and demonstration of new technologies as well as those that generate demand and support the diffusion of innovations on the market. In addition, the transformation of the energy system can be supported by applying systemic instruments that promote the functionality of the innovation system.

As part of the German *Energiewende*, the German government has now set itself the objective of increasing the share of renewable energy sources in power generation to at least 80 percent by 2050. A mix of instruments, which is being continuously enhanced, is used to achieve this objective. The German Renewable Energy Sources Act (EEG) is considered the core instrument for reaching this expansion target. Its impact on innovation and its joint effect with public research funding were the subject of scientific debate last year. However, the impacts of the overall policy mix beyond this joint effect were not sufficiently considered. In this context, the GRETCHEN research project examined the impacts of the German policy mix on the development and diffusion of renewable power generation technologies as well as on the resulting technological and structural change.

A **policy mix concept** that combines approaches from environmental and innovation economics and political sciences was developed during the first stage of this research project as the basis for the subsequent empirical studies. Figure 1 shows the three resulting building blocks of the GRETCHEN policy mix concept: Elements, processes, and characteristics that can be specified individually using different dimensions. The studies focus on the elements of the policy mix which include political strategies with their long-term objectives and plans for action (such as for the

Figure 1: GRETCHEN policy mix concept [15]



Energiewende, for example), but also on the mix of interacting instruments (e.g. the EEG, public R&D funding and the EU Emissions Trading System). These different elements of the policy mix are determined in political processes – in Germany at both, the federal state and the national level – as well as at the European level and internationally. In addition, the characteristics of the policy mix are explicitly taken into account in GRETCHEN. These include not only the consistency of the policy strategy and the instrument mix, but also the coherence of political processes, as well as the credibility and comprehensiveness of the policy mix.

Based on this overarching policy mix concept, empirical analyses took place on three levels:

- At the **micro level**, the company-specific impacts of the policy mix on inventions, innovations and the diffusion of technologies for renewable power generation were examined with the help of company surveys and patent data analyses.
- At the **meso level**, the focus was on the impacts of the policy mix on innovation systems and technology development in the field of renewable power generation technologies (especially wind power and photovoltaics). Additionally, the influence of the policy mix on the industry structure in photovoltaics was analysed for Germany while taking interactions with China into account.
- At the **macro level**, the technological change in renewable power generation technologies was modelled endogenously. The macroeconomic effects of the policy mix and its impacts on emissions were identified using scenario analyses.

This approach reveals the relationships between the policy mix for renewable power generation technologies and the corresponding technological and structural changes. The following chapters summarise the project results of the three-and-a-half year GRETCHEN project for decision-makers from politics, industry and research. After a review of the market and technology development of renewable energies in the field of electricity generation (Chapter 2), Chapter 3 presents the policy mix for Germany in more detail. Chapter 4 describes the effect of this policy mix on innovation and technological change. Reference is always made to the scientific articles produced as part of GRETCHEN that include more information and are listed in the bibliography. In addition, throughout the report, boxes provide concise explanations of the methodology used. Finally, based on the project results, Chapter 5 draws general conclusions for policy makers about the design of the policy mix and identifies future research needs.

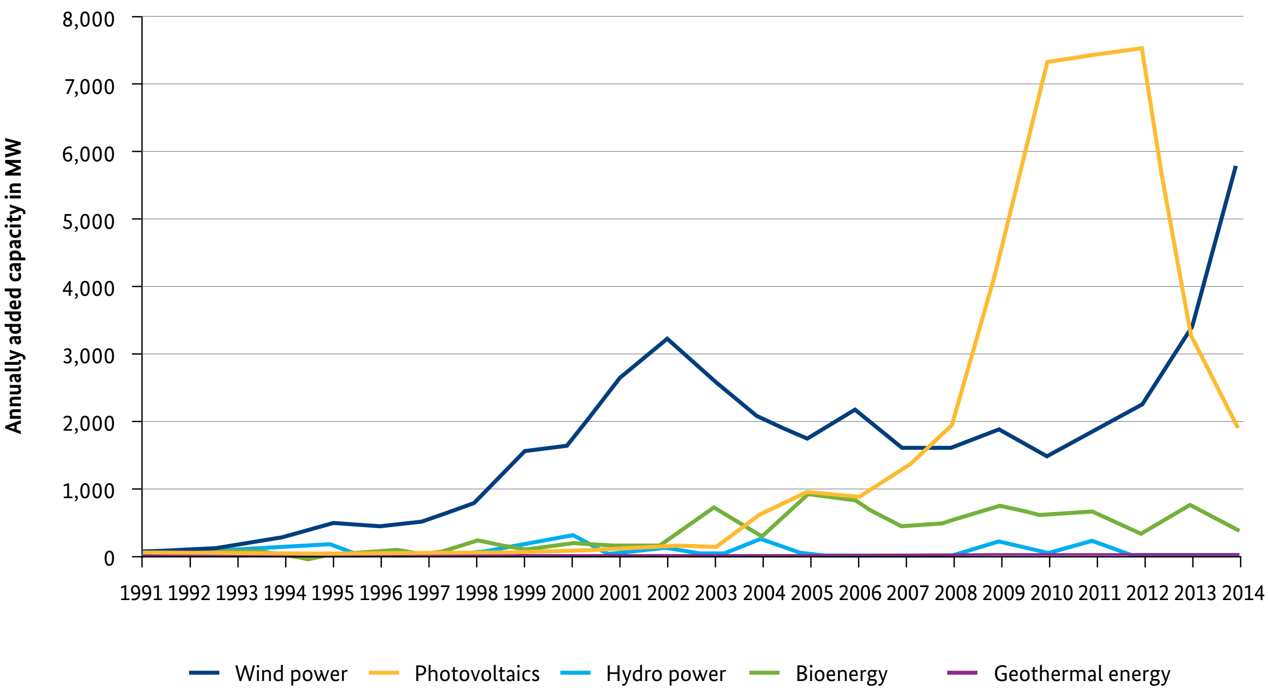
2 Market and technology development of renewable power generation technologies

2.1 Market development

Renewable power generation technologies have gained importance, not only in Germany, but also globally, and have influenced the power market and the structure of industry.

The **expansion of renewable power generation technologies in Germany** is technology-specific (cp. Figure 2). Wind power has been installed the most, with a peak in 2002. Subsequently, its expansion slowed down only to rise sharply again from 2012, although this has been strongly influenced by offshore development with a 25 percent share in 2014. Photovoltaics development increased strongly from 2003 and experienced a boom from 2008 until 2013, although this expansion boom ended abruptly in 2013. From 2000, there was also an increasing use of bioenergy to generate power. This energy source is capable of providing base load, but the expansion figures remain moderate when compared to wind power and photovoltaics. There has been very little growth in geothermal energy and hydropower which is probably due to the low level of state support for geothermal and a lack of suitable locations for hydropower. Other technologies, such as solar thermal power stations, wave or tidal energy are not relevant in Germany.

Figure 2: Annually installed capacities of renewable power generation technologies in Germany [BMWi 2015: Time series on the development of renewable energies in Germany]



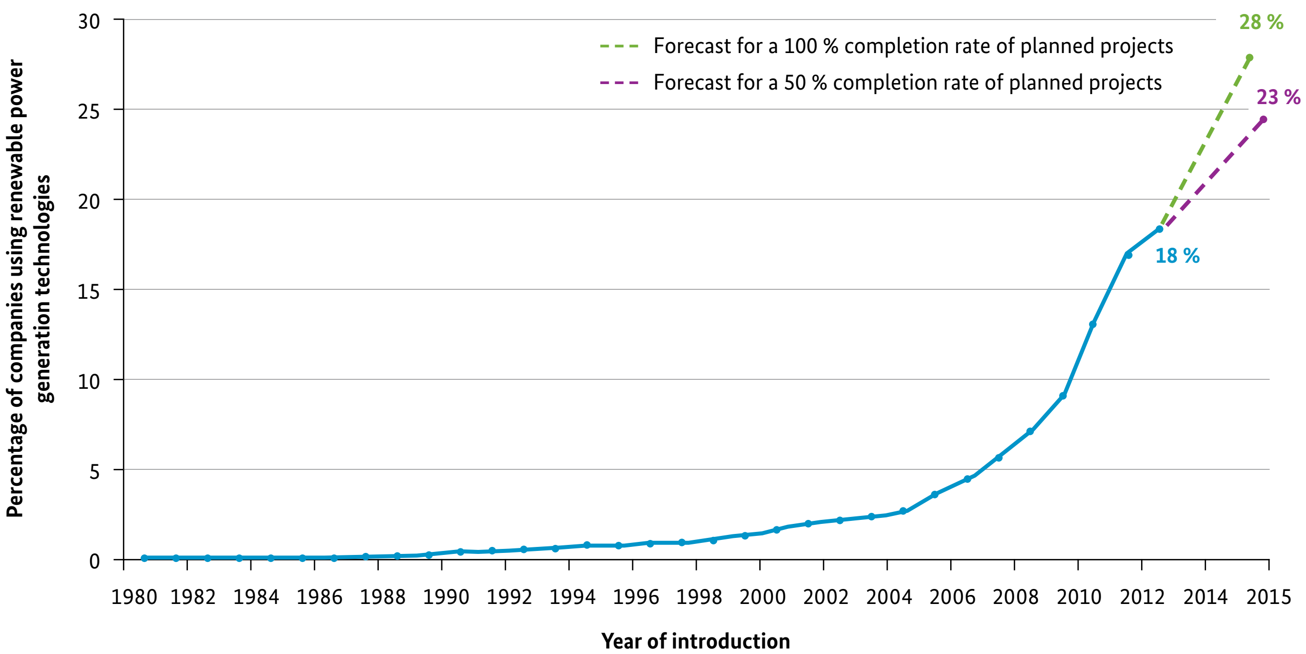
Box 1 Company survey *German Manufacturing Survey 2012*

The Fraunhofer ISI has been conducting regular surveys of production trends since 1993. The 2012 survey covers all manufacturing sectors. The survey includes questions about production strategies, the use of innovative organization and technology concepts in production as well as recording performance indicators like productivity, flexibility and quality. This wealth of information enables the survey to make detailed analyses of how modern manufacturing enterprises are and their performance capacity. 1,594 manufacturing companies in Germany returned a usable questionnaire in the 2012 survey. These enterprises are representative of Germany's manufacturing sector [8].

One big advantage of renewable power generation technologies is the possibility to install small systems directly at their users. In order to estimate how much these are being used so far in industry and their future developments, a **survey of the manufacturing sector** was conducted in Germany as part of the GRETCHEN project [8, 17]. The Fraunhofer ISI's German Manufacturing Survey 2012 was used here (see Box 1 Company survey *German Manufacturing Survey* 2012). Figure 3 illustrates the diffusion of renewable power generation technologies in the manufacturing sector. In 2012, 18 percent of the surveyed companies used renewable power generation technologies. By 2015, this share could rise to 28 percent – if companies actually implement all their planned projects to use renewable power generation technologies. Even if only 50 percent of the planned projects are realised, this would still result in a share of 23 percent.

Resource availability in the form of solar radiation could be identified as one factor influencing the adoption of

Figure 3: Diffusion of renewable power generation technologies in the manufacturing sector [8]



renewable power generation technologies. It was shown, for instance, that companies in sunnier regions of Germany (the federal states of Bavaria, Baden-Wuerttemberg, Berlin, Saarland and Rhineland-Palatinate) are more likely to invest in renewable power generation technologies than those in less sunnier states. In contrast, there are no differences between companies in energy-intensive sectors and those in non-energy-intensive ones. Furthermore, companies with close ties to final customers tend to use renewable power generation technologies more often to accentuate their "green" image.

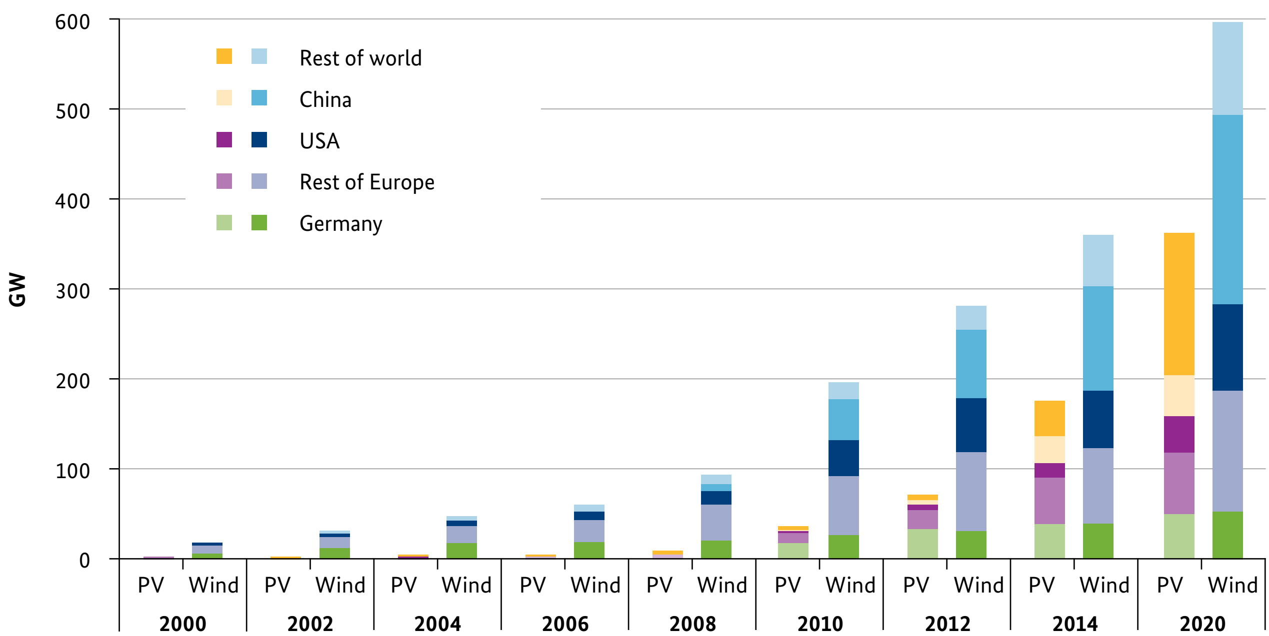
The **total capacity worldwide** in 2014 was 361 GW for onshore wind power and 175 GW for photovoltaics. This means the globally installed capacity of wind power has increased six fold over the last 10 years and that of photovoltaic by the factor of 40.

In terms of global market development, Germany's share of installed photovoltaic capacity was 46.5 and 49.4 percent in 2006 and 2010, respectively, while its share in wind power for the same time dropped from 31 to about 14 percent. Even before 2015, Germany's lead in expanding renewable power generation was increasingly being challenged by other countries, especially the USA and China (see Figure 4).

As part of GRETCHEN, the global **expansion of renewable power generation technologies** was estimated **until 2020**. Learning curves were used to project cost development (see 2.2) and country-specific investment costs were used to determine additional capacity deployment in photovoltaics and wind power [20]. Global capacity increases will remain strong until 2020, but there are variations in the development paths expected for individual countries and regions. China, in particular, is massively expanding its wind power capacities [22], whereas the clear global growth in photovoltaics, which is rapidly catching up with wind power, is spread across many different countries [19].

The global expansion of renewable power generation technologies offers German manufacturers promising **export opportunities**. According to the GRETCHEN survey (see Box 2 GRETCHEN survey 2014), nearly 90 percent of the manufacturers located in Germany exported their products abroad in 2013. The export share of companies' turnover was almost 40 percent on average but differs by technology, although photovoltaics and onshore wind power are not far apart with 41 and 47 percent, respectively [12]. The large majority of companies said the EU and EFTA countries were their main export market. One third of the companies are also active in China, India and the US. Half of the companies also sell their products in many other

Figure 4: Globally installed wind power and photovoltaic capacities by country – historical development and projection up to 2020 (in GW) [20, 21]

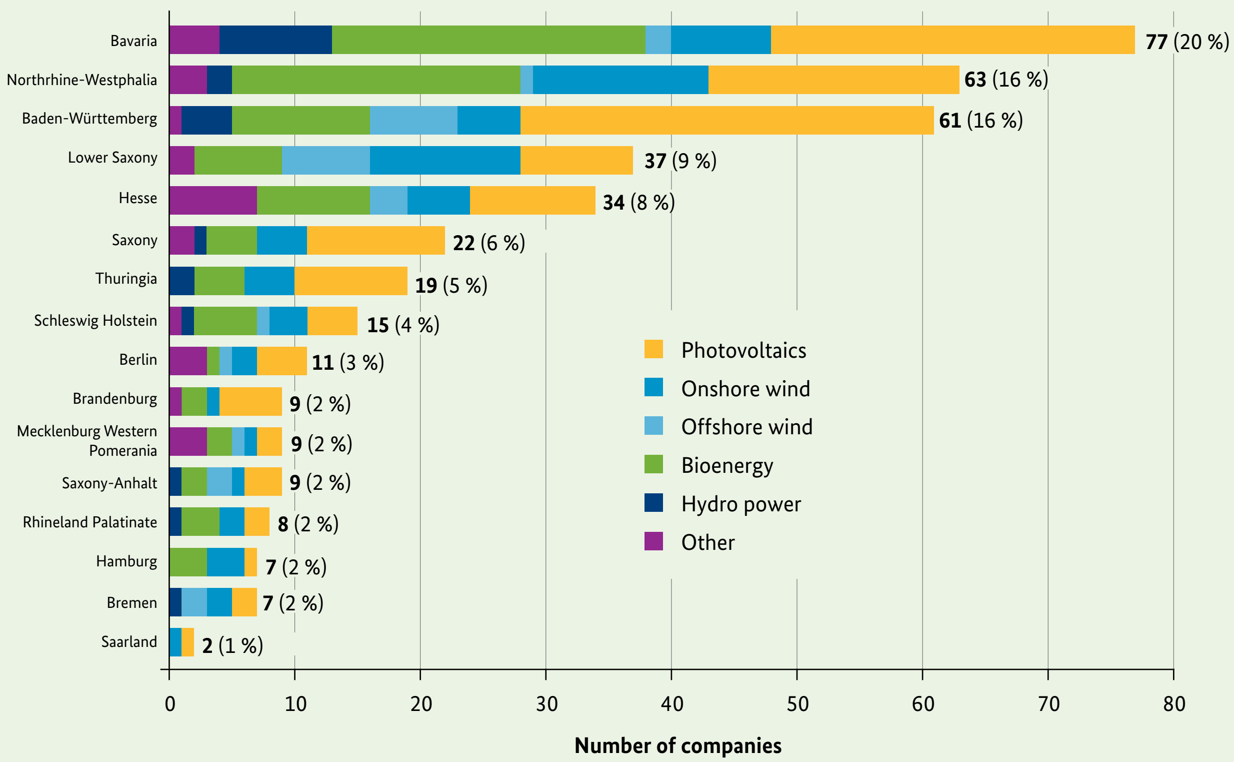


Box 2 GRETCHEN survey 2014

Within the GRETCHEN project, a telephone survey was carried out with questions about the innovation activities of the manufacturers and suppliers of installations and components for renewable power generation technologies in Germany. The objective of this survey that was conducted during the summer of 2014 was to understand the effects of the political framework conditions on the innovation activities of manufacturers based in Germany. A questionnaire was developed for this purpose that is based on the Europe-wide Community Innovation Survey and supplements this with a block of questions concerning the policy mix. The SOKO Institute for Social Research and Communication in Bielefeld was given the job of conducting the telephone survey.

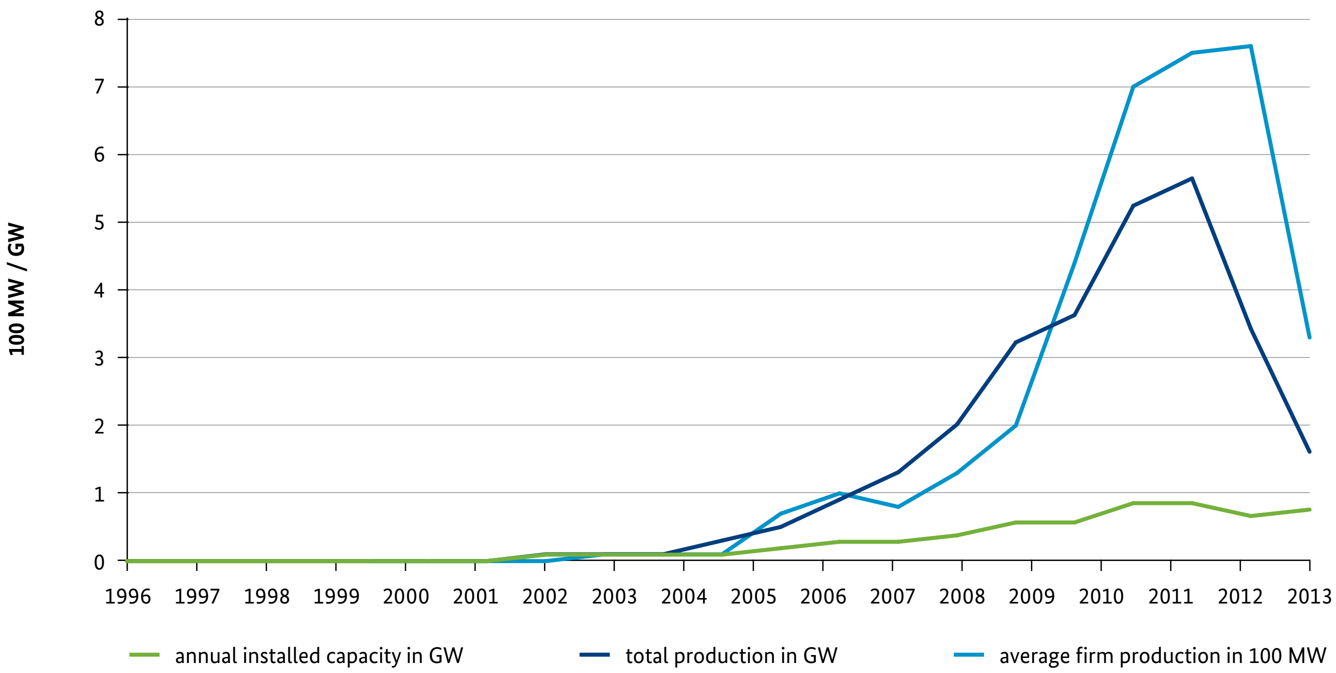
In total, 390 manufacturers took part in the roughly 30-minute survey. This figure corresponds to a good third of the manufacturers based in Germany. These are mainly small and medium-sized enterprises (up to €50 million turnover and 249 employees). Two thirds of the businesses focus on one renewable power generation technology, while the other third made products for at least two (17 percent) or more than two technologies (16 percent). About half of the manufacturers are active in photovoltaics (46 percent), followed by biogas (30 percent), onshore wind power (26 percent), offshore wind power (20 percent) and hydropower (16 percent). Other technologies (solar thermal power stations, biomass plants, marine energy technologies, geothermal and others) play a subordinate role with a share of about 25 percent in total. As shown in the diagram, according to the GRETCHEN survey, in 2014, more than half the enterprises were located in the three German federal states of Bavaria, Baden-Wuerttemberg and North Rhine-Westphalia, the four states of Lower Saxony, Hessen, Saxony and Thuringia are home to another 30 percent of the businesses.

Participants in the GRETCHEN survey by German federal state and main technology [12]



It is evident that over 80 percent of manufacturers performed innovation activities in the period 2011-2013; the main focus here was clearly on in-house R&D activities [12].

Figure 5: Development of the average and total production of PV module and cell manufacturers and the annually installed capacity in Germany (1996-2013) [3]



countries, which could prove to be a strategic advantage in light of the 2020 projections (cp. Figure 4).

The development of the **industrial structure of Germany-based manufacturers** of renewable power generation technologies is illustrated based on the example of photovoltaics [3]. To start with, a few companies entered the market as the use of photovoltaics expanded in the 1990s. The number of manufacturers grew rapidly from 2001, although a process of consolidation has clearly taken place since 2012. The annual production of modules and cells increased over time and peaked in 2010. This was accompanied by an increase in average production, although companies developed very heterogeneously in terms of size. Figure 5 shows the development of production and additional installed capacity in Germany. While production exceeded additional installed capacity until 2008, domestic producers were no longer able to completely cover the demand thereafter. Although German production continued to grow in the next three years, Chinese producers increasingly entered the global market from 2005 and had expanded their production up to 20 GW by 2011. Lowered feed-in tariffs in Germany and the corresponding drop in demand combined with competition from China led to a radical slump in production both in Germany and in China after 2011 [22]. The recent development of average production shows that both small and large manufacturers are affected by this negative market trend.

2.2 Innovation and technological change

Transforming the energy system into sustainable, CO_2-neutral electricity production requires the development of new technologies and the further development of existing ones. The technological change resulting from this process can be illustrated using different **indicators along the innovation process**. This process starts with basic and applied research codified in scientific publications and leads to inventions that are often protected by patents. The innovation process culminates in specific product and process innovations at the manufacturers. These can be measured indirectly through efficiency improvements in production. Cooperation plays a major role in all phases of the innovation process. This is reflected by co-authorships or co-application of patents and collaborative research projects (see Box 3 Research and innovation networks). An upward trend of all these indicators over time documents the increase of such activities that can contribute significantly to the transformation of the energy system.

Scientific publications map the results of academic basic research as well as applied research. There has been a clear rise in the number of publications concerning photovoltaics research in Germany (cp. Figure 6). In an international comparison, Germany has always been among the top five publishing nations in the field of photovoltaics research, although several Asian countries have recently closed the gap and are now also ranked among the world's best. At European level, Germany remains the leader.

The **cooperative activities of researchers** in Germany have also increased greatly over time. As an example, Figure 7 shows the network of actors publishing in Germany for the years 1999-2001 and 2004-2006. The size of a circle (actors from Germany) or square (actors from abroad) indicates the number of cooperations. It is obvious that the number of actors and cooperations has grown rapidly in this short period. Especially universities and research institutions are very well connected nationally and internationally; foreign universities are often the main new cooperation partner. These international cooperations result in the integration into the international research landscape and provide access to external knowledge. Compared to other countries, German photovoltaics research is very well connected internationally [5].

Box 3 Research and innovation networks

Knowledge transfer and cooperative research play an important role in innovative activity. It has often been shown that cooperation leads to more and higher quality innovations. Functioning innovation systems basically rely on this effect. There are different kinds of cooperation that can be represented as networks. Three different cooperative networks were analysed as part of GRETCHEN:

- **Publication networks** map the interrelations between co-authors of scientific publications. Different levels of aggregation can be regarded. In GRETCHEN, the relations between the authors' affiliations are captured as well as the countries in which the authors live. These dimensions provide information about the flow of knowledge among the research organizations and across national borders [5].

- **Patent networks** link the inventors of jointly developed patents (co-inventors). This illustrates the knowledge exchange among inventors [4].

- **Research networks**, link actors via jointly funded projects (so called cooperative research). These research networks provide an insight into the cooperative research landscape in Germany and indicate how well the innovation system is functioning [6].

Figure 6: Number of scientific publications concerning photovoltaics in selected countries [5]

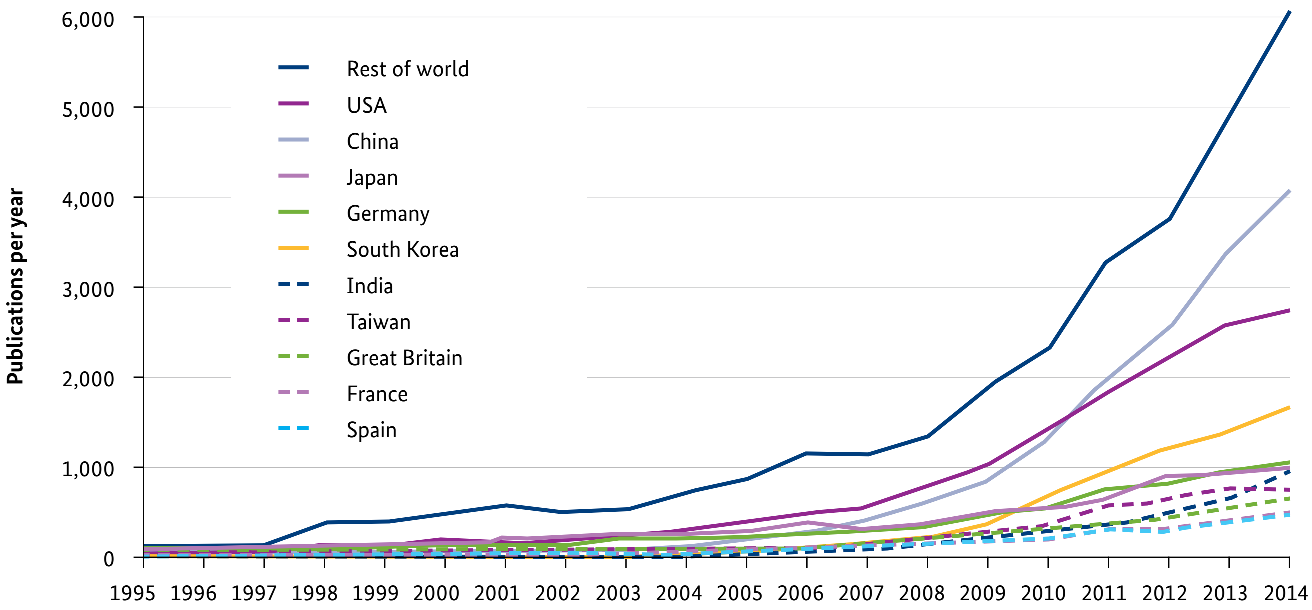
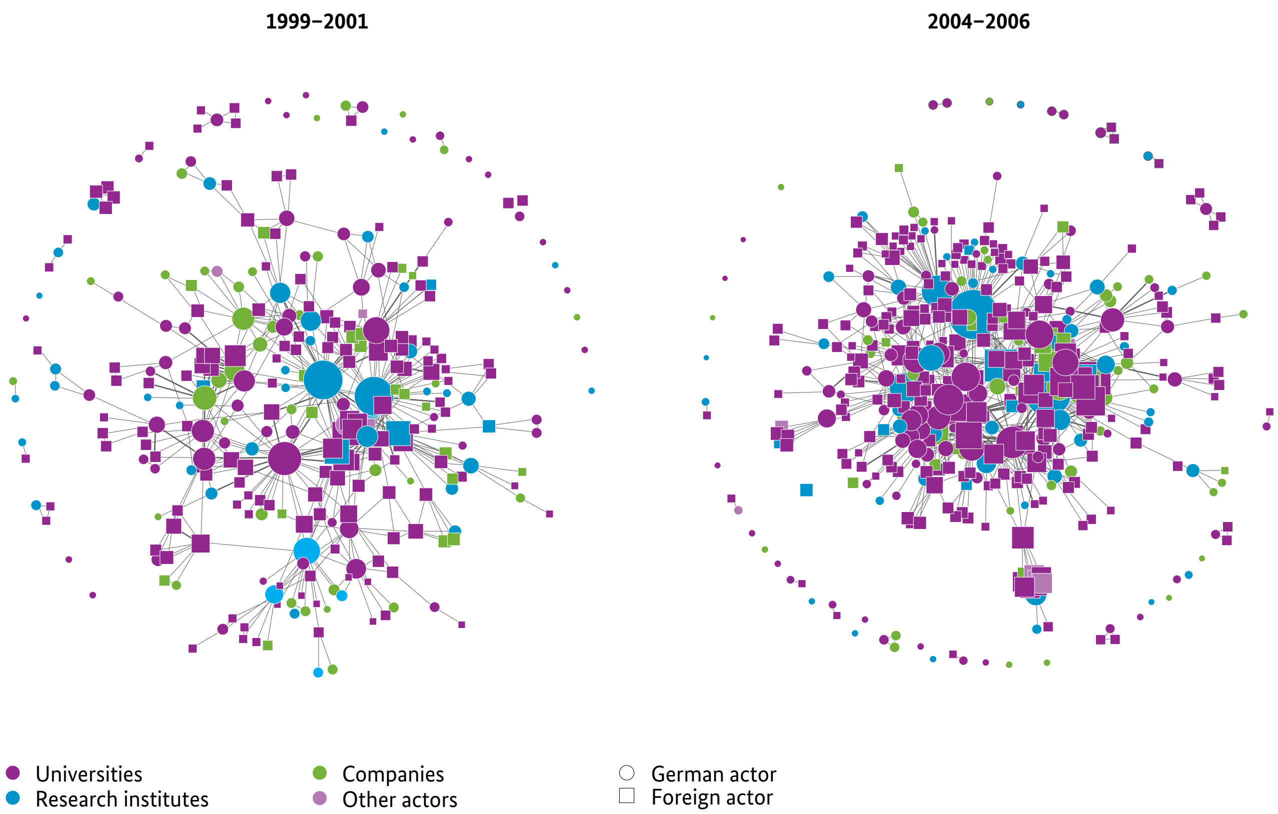


Figure 7: Photovoltaics publication networks in 1999–2001 (left) and 2004–2006 (right) [5]



Box 4 Patents

Patent applications are not a perfect indicator but are commonly used because of the availability of standardised documentation over long periods of time. Patents may only be able to illustrate parts of technological change because patent applications are associated with costs, so patents are only applied for if the invention promises a certain economic value.

The patent data illustrated in Figure 8 are so called Patent Cooperation Treaty (PCT) patents, i.e. patents that have been submitted for examination to the World Intellectual Property Organisation (WIPO). PCT applications are particularly suitable for international comparisons since there are hardly any distortions to national patent offices. However, they do not record all the patents of a country as only some of the patent applications are submitted to the WIPO. The patent data for wind power and photovoltaics were retrieved according to the WIPO Green Inventory.

Within the GRETCHEN project, different query methods were developed for different purposes and the data were processed accordingly for the respective research questions. Overall, the different query methods result in very similar patent trends, but they differ with regard to the respective quantity of patents [1, 3, 4, 6].

Compared to scientific publications, **patents** document the results of research with a stronger focus on application (see Box 4 Patent). The number of German inventors of globally registered patents for wind power and photovoltaics was relatively low up to the mid 1990s, but subsequently increased steadily – and to a greater extent than the general patent trend in Germany [4]. However, it should be noted that patents do not cover the entire spectrum of knowledge generation. According to the GRETCHEN survey, in the period 2011-2013, Germany-based manufacturers of renewable power generation technologies used patents to protect about half of their inventions in photovoltaics and wind power [12].

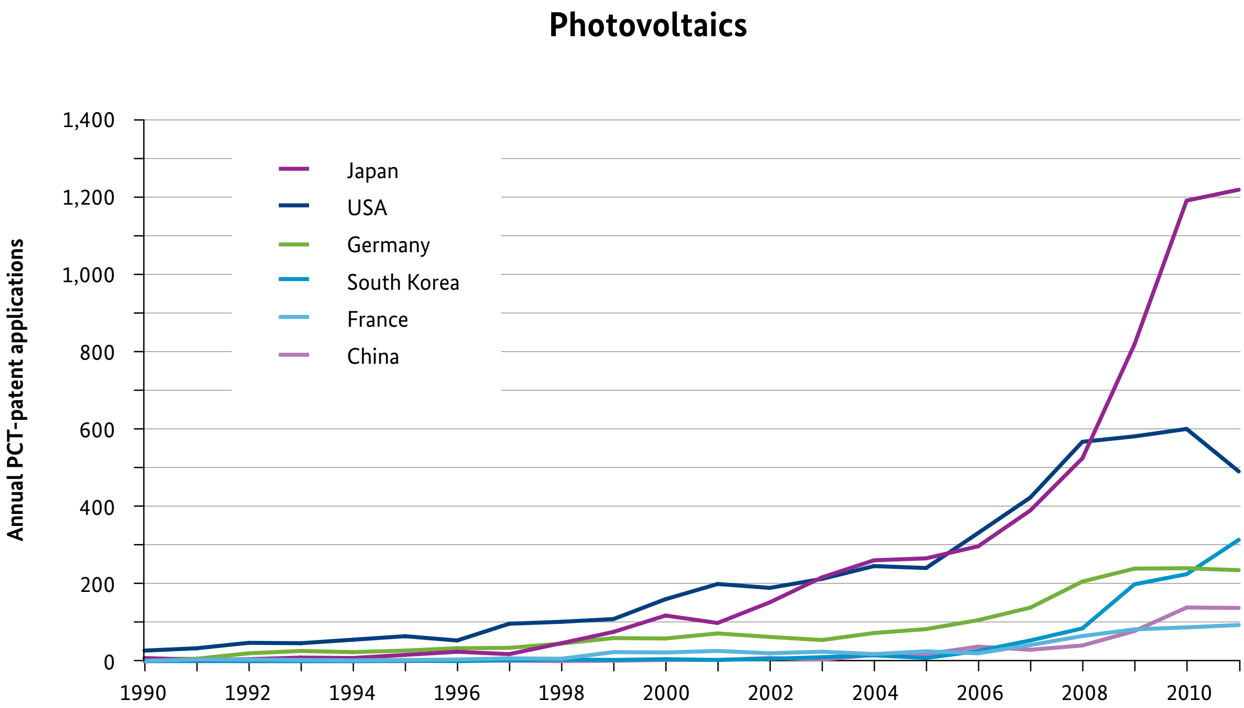
In an international comparison of the number of wind power patents (see Figure 8), Germany was in second place behind the USA for a long time, but has recently been able to take the lead. It is interesting to note the significant increase in patent applications from Asian countries, especially from Japan, China and South Korea. Concerning the number of patents in photovoltaics, Germany was in third place for a long time, clearly lagging behind the USA and Japan, and has recently been overtaken by South Korea as well.

A closer analysis of all the German patenting actors in the field of photovoltaics shows that a large share of patents is registered by companies and individuals. The share of research institutions and universities drops over time from 15 percent to about 10 percent. A differentiated analysis reveals a much stronger increase in German photovoltaics patent applications for module and cell manufacturers than for other applicants from 2007 onwards [3].

Similar to publications, the analysis of patents shows increasing **cooperation** in wind power and photovoltaics over time. The cooperation between German inventors in photovoltaics is much stronger than the cooperation in wind power. Furthermore, a core network gradually emerges for both technologies over time, in which many actors interact with each other. This is an indication of significant knowledge exchange [4].

Technological change can be documented directly using **product and process innovations**. According to the GRETCHEN survey, three quarters of the manufacturers of renewable power generation technologies introduced product innovations in the years 2011-2013, and two thirds of them process innovations. As Figure 9 illustrates, an above-average number of product innovations were introduced in onshore wind, bioenergy and photovoltaics, while process innovations show no major differences between technologies. Corporate funds were invested to create these innovations. However, figures for the period 2013-2015 indicate the emergence of a negative trend for company expenditure on innovation [12].

Figure 8: International patent applications for photovoltaics and wind power
[taken from the OECD Regpat 2015 database]



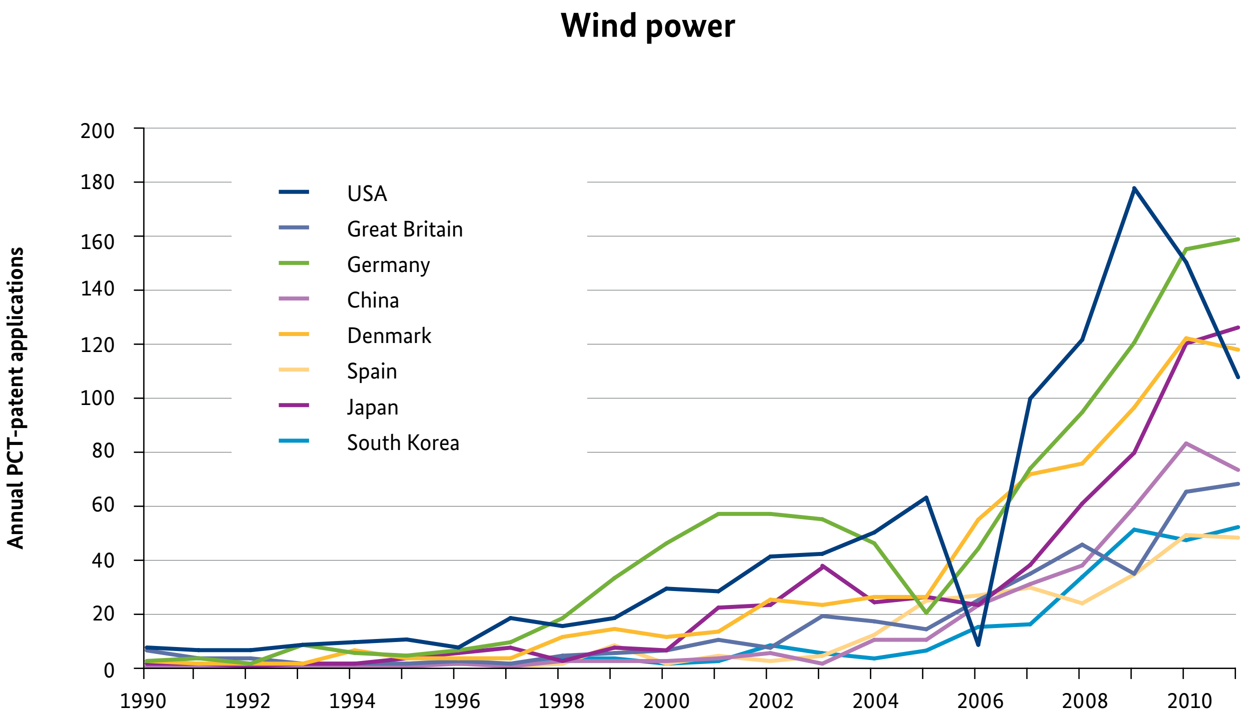
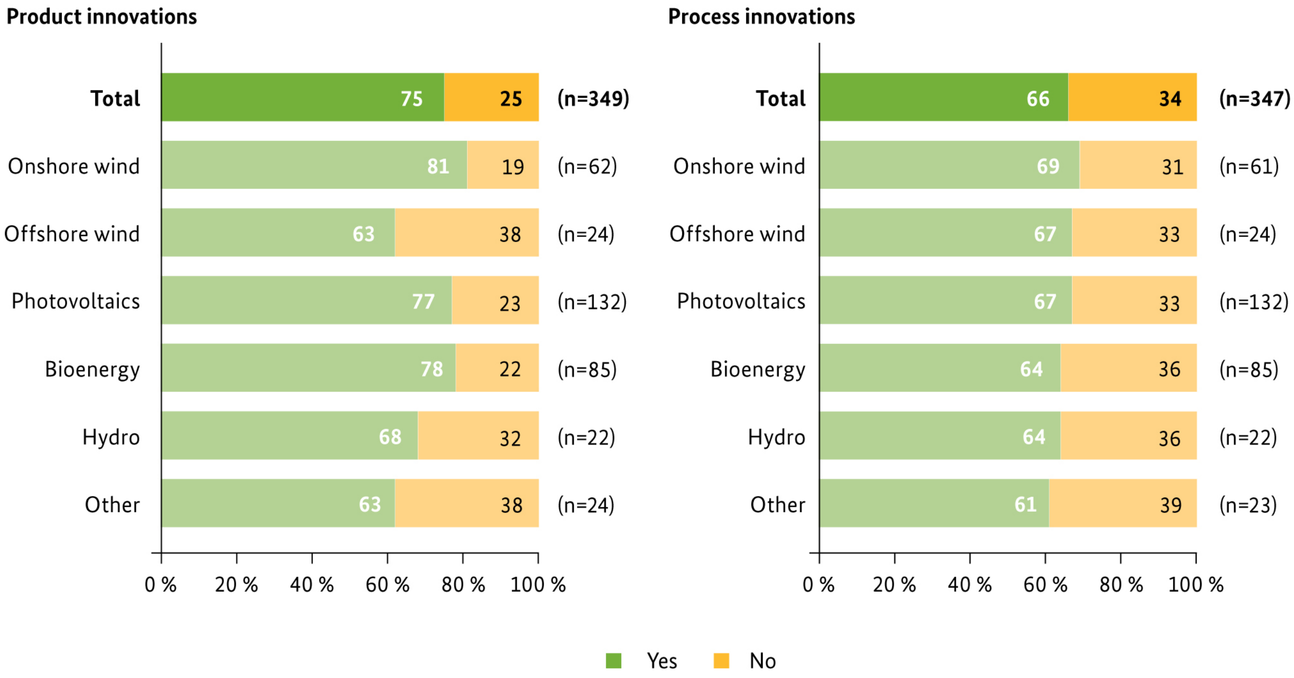


Figure 9: Technology-specific product and process innovations [12]

During the three years 2011 to 2013, did your company introduce new or significantly improved products or processes in the renewable energy branch?



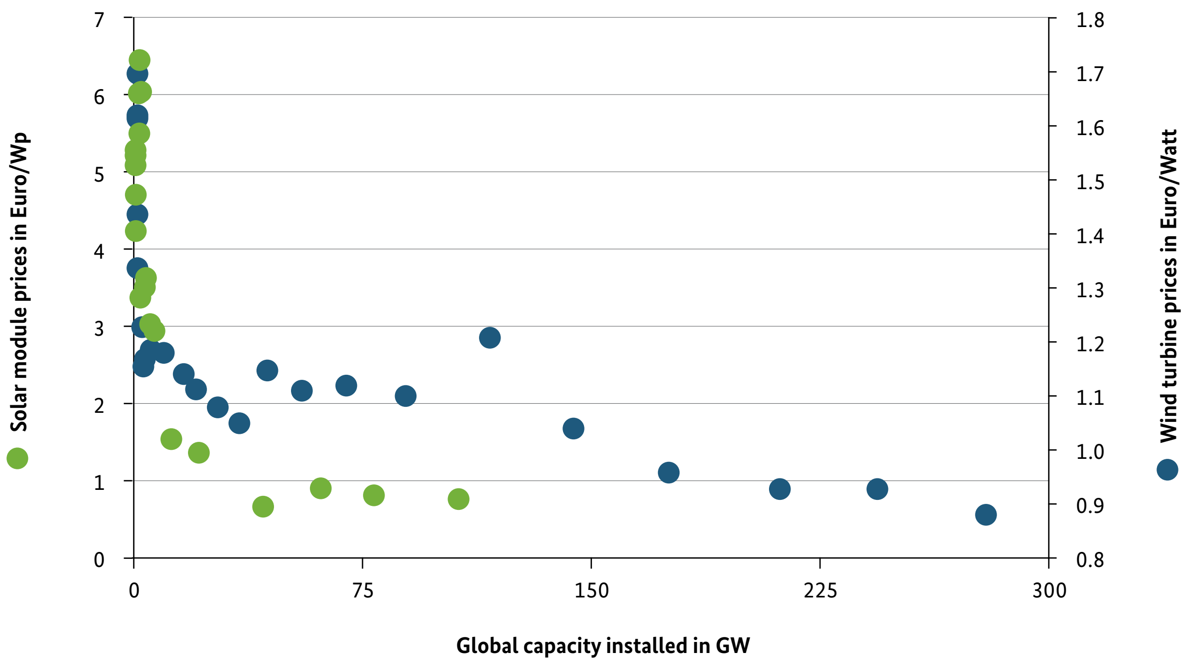
Companies do not carry out innovation activities in isolation, but enter into **research cooperation** with other enterprises or research organizations. About half of the surveyed companies, for instance, said they had been involved in research cooperation in the period 2011 to 2013. Such past cooperations can be mapped by looking at publicly funded joint research projects which provides insights into the innovation system in which the companies are active. Universities and research institutions occupy a key position in this system and have numerous cooperative links with companies. In the last ten years, 70 percent of funding has been assigned to research consortia featuring at least one company. This shows that companies are assisted complementarily by public actors who support research and development in the private sector [6].

The development of technology costs is often depicted by **learning curves** (see Box 5 Learning curves). The development of technology costs has been estimated for wind turbines and photovoltaic modules based on data for the

Box 5 Learning curves

Learning curves can be determined by analysing technology development over time using the costs for one energy unit such as € per megawatt, for instance. These clearly reveal the cost reduction that can be achieved through different factors such as economies of scale, increased competition or improved production processes. Single- or two-factor learning curves are the most common that illustrate the cost development of technologies related to global expansion (learning-by-doing) and to research efforts (learning-by-researching). The single-factor learning curves assume that the costs of the technology decline by x percent with every doubling of output, where x is defined as the learning rate.

Figure 10: Technology costs and globally installed capacity of wind turbines and solar modules (1990–2014) [20]



period 1990-2011 (displayed in Figure 10) [20]. The learning rates of about 4 percent for wind power turbines and about 17 percent for photovoltaic modules are rather conservative. It should be noted that the global cumulated capacity of installed photovoltaic-based power generation plants was an important cost curbing factor during 2011/12. Despite considerable cost reductions over the past years, manufacturers of renewable power generation technologies still see clear innovation potentials (in geothermal, tidal power stations, photovoltaics and offshore-wind among others) according to the GRETCHEN survey. It can be assumed that the cost of generating electricity from renewable power technologies will continue to decline in the future.

2.3 Structural change and macroeconomic effects

The fuel mix of power generation and the related economic structures change due to market and technology development and the resulting expansion of renewable energies.

A shift is taking place from conventional large power stations toward smaller, more decentralised generation. For the growing number of these new plants, especially German manufacturers are supplying intermediate products and components across the entire value chain. The GRETCHEN survey shows that a bit more than 70 percent of the manufacturers of renewable power generation technologies produce components, while only about a third of companies also make final products.

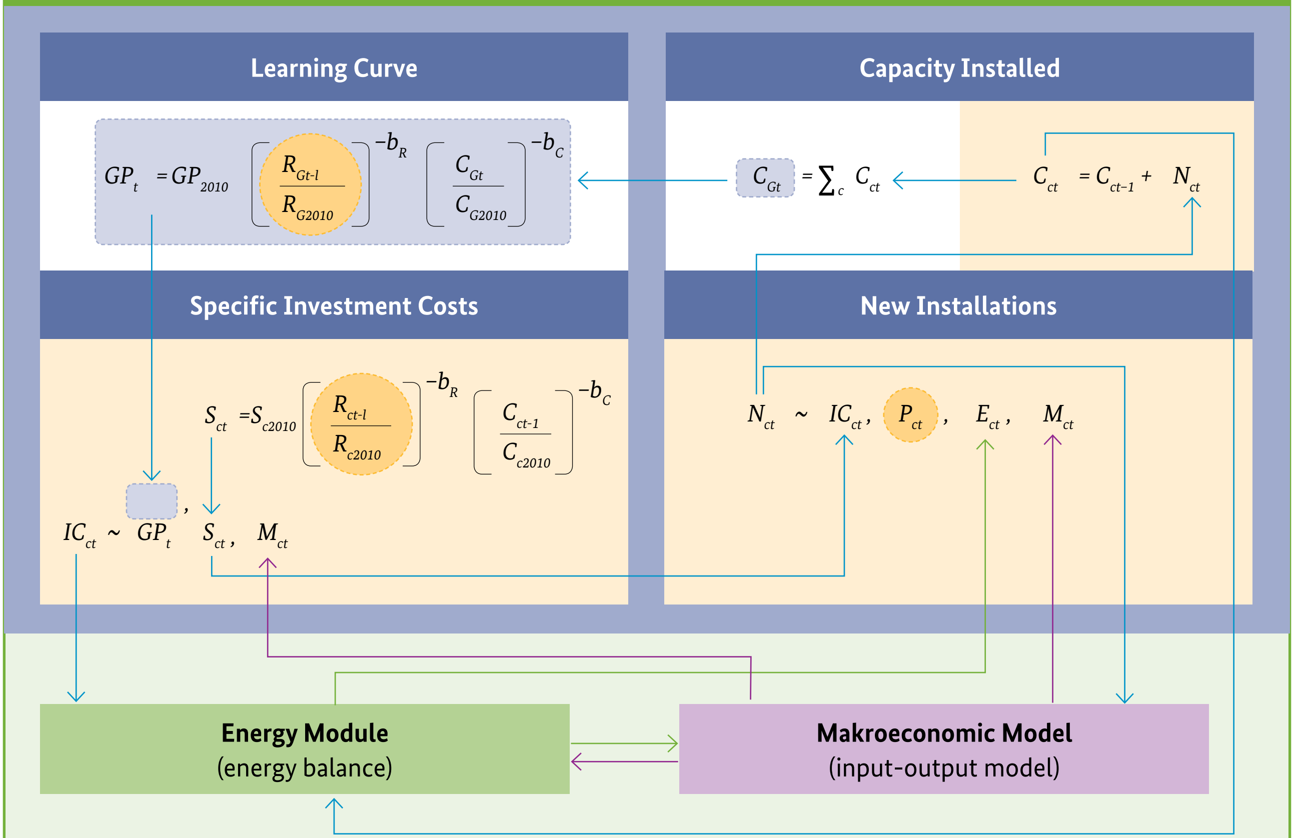
The **macroeconomic effects** and indicators – such as employment, gross domestic product (GDP), investments and CO_2 emissions – of expanding renewable power generation are estimated/modelled using scenario analysis. Comparing alternative scenarios with different impulses (uniform domestic expansion, variants in terms of export development; see Figure 11) with a reference development (counterfactual scenario without expansion) shows the effects of the expansion in the macroeconomic modelling framework including different second-round and feedback effects [7, 18].

Box 6 Endogenisation of technological change in the GINFORS_E model

The macro level modelling developed in GRETCHEN, the RPGM module of GINFORS_E, is shown in the figure below. It illustrates the complex steering mechanism against which national energy policy has to create reliable boundary conditions for investors. The policy mix in all (important) countries influences the development of global learning curves through new installations. The resulting increase in global capacity installed in turn reduces the specific investment costs in every country, which positively influences deployment as well. The GINFORS-E modelling approach has been significantly enhanced within GRETCHEN [20] to better represent this complex, global process, which is accompanied by different structures, policy instruments and feedback loops in the individual countries. The feedback into the macroeconomic input-output system is modelled for those countries producing wind and photovoltaic technologies by adjusting the intermediate input structure [18]. This particularly concerns the machinery and equipment and the electrical machinery and apparatus industries. In countries using renewable power generation, the electricity mix shifts away from fossil energy sources, thus changing inputs into electricity generation.

Different aspects of the policy mix are represented in the macroeconomic modelling: the dimensions include innovation, energy and climate policy in Germany and at EU level, the OECD countries and their major trade partners, different technologies (photovoltaics and wind power) and therefore different industries [21]. The entire value chain is examined indirectly using input-output models [18].

Structure of the module for renewable power generation (RPGM) [20]



C: Capacity installed
N: New capacity installed
GP: Global turbine/module price
S: System costs
IC: Specific investment costs
R: public R&D
P: policy variables
M: economic model variables
E: energy module variables

c: country index
G: global
t: time index

Individual countries
Global variables
Possible policy influence

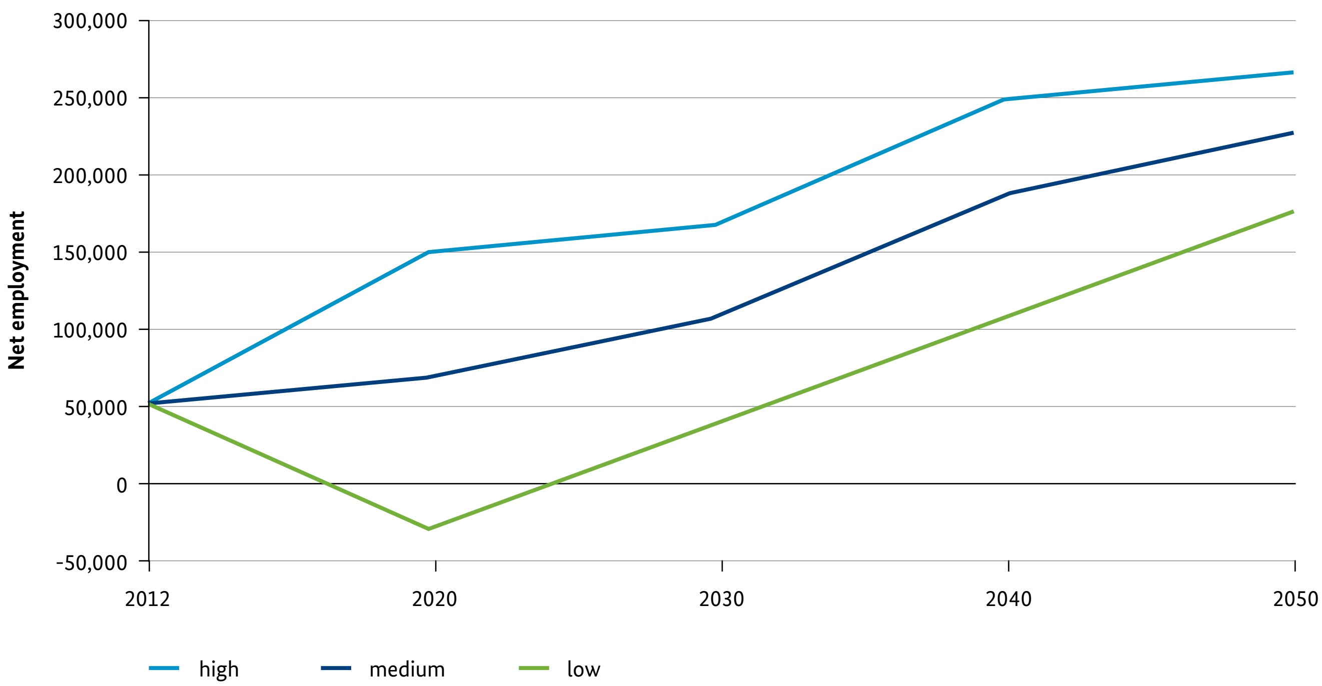
The scenario analyses show that, in a purely **national perspective**, the macroeconomic effects of expansion in the short term are mainly due to additional investments. In the longer term there are electricity price effects due to the rising EEG surcharge. Particularly electricity-intensive enterprises are exempt from this. Different distributional effects are associated with the different investment options and price effects. Other long-term effects result from operating and maintaining the plants. Overall [7]:

- There is a positive effect on demand for the years 2009 to 2012 on account of the strong growth in photovoltaics at this time. As a result, total investments are more than 15 billion euros higher than without the expansion of renewable power generation. The effects on GDP (more than 10 billion euros) and employment (50,000 to 100,000 additional jobs) of expanding renewable energies are also positive in this period.
- In subsequent years, from 2014 onward, the rising EEG surcharge has a negative cost effect that, in a purely national perspective, also has slightly negative effects on GDP and employment. The burden on the conventional power sector due to expansion is currently clearly visible in the poor business results and dark future prospects of the large utility companies.
- Even in the most favourable case, the additional CO_2 emission reduction of an accelerated expansion is less than 2 percent of total emissions up to 2030, and is very low until 2020 [21].

This picture changes if the **international dimension** of expansion is included, because German manufacturers are well positioned on the markets for renewable power generation technologies (cp. Figure 11):

- If it is taken into account that current and future exports are also consequences of the German policy mix, then the resulting macroeconomic effects are positive in most cases, even in the medium term, and, in the long term, reach levels well above 100,000 additional jobs.
- Negative GDP and employment effects in the medium term (2020) only result under very pessimistic assumptions about the international expansion of renewables and the market shares of German manufacturers. Figure 11 shows three senarios of international expansion. The scenario of "low" international expansion assumes significant decreases in Germany's exports of renewable energy technologies for the future compared to the current situation. This "low" scenario is not a probable one, because it implies that German manufacturers would have to accept an absolute decline in exports on the rapidly growing international market.

Figure 11: Net employment effects of expanding renewable energies under different assumptions about how exports of German installations develop (high – medium – low) [7]



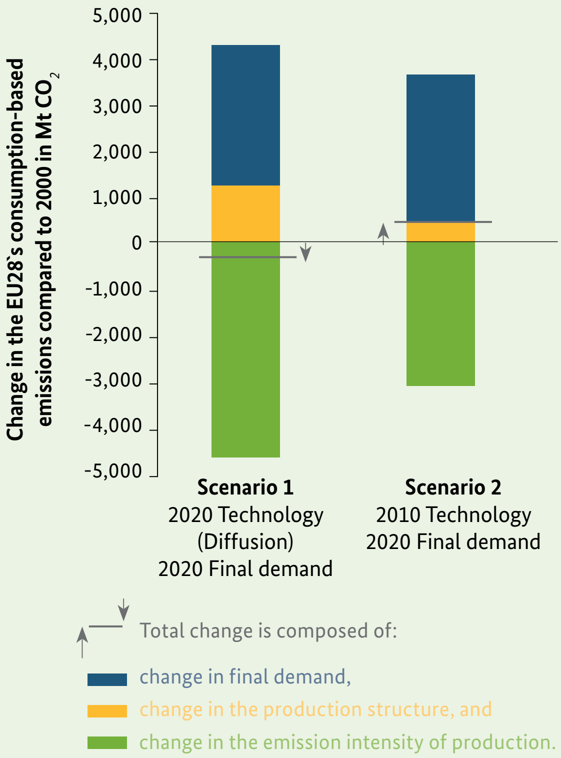
The development of global costs, especially of photovoltaic modules, has been strongly influenced by the deployment of RPGTs in Germany (see Figure 4), but also by Germany's public R&D support for the technologies. The falling costs of the technologies have directly influenced the increased global expansion (see Box 6 Endogenisation of technological change in the GINFORS_E model), which in turn has led to further cost reductions (see Box 5 Learning curves). Germany's policy mix for renewable energies has therefore indirectly influenced the expansion of renewable energy technologies in other countries, even if this influence has perhaps only been marginal and indirect [19]. It contributes to decarbonising electricity generation. Emissions will decrease in the EU countries and remain constant in the other OECD countries in spite of increasing production. In the BRICS countries (Brazil, Russia, India, China and South Africa), which account for a large share in the global growth of CO_2 emissions, weak decoupling of production and emissions can be observed: the CO_2 emissions increase half as quickly as production [18, 19].

This result may also contribute to a related but slightly different policy discussion. When analysing **consumption-based CO_2 emissions** (see Box 7 Consumption-based emissions), it becomes clear "that the major source of emissions along global production chains is the electricity industry. Thus, for reducing not only territorial but also consumption-based emissions in the future, the importance of the diffusion of renewable power generation technologies worldwide is inevitable" [19]. Given the big share of Germany in global capacity installations of wind power and photovoltaic technologies together with the concept of learning-by-doing and corresponding cost reductions, it can be inferred that the German policy mix (enhancing capacity installations) has played a major role in decreasing global average technology costs, thus enabling a faster worldwide diffusion of these technologies. This in turn has a positive impact on reducing German consumption-based emissions.

Box 7 Consumption-based emissions

The concept of consumption-based emissions assigns the emissions occurring along global production chains to the country of final consumers. This way of allocating emissions is complementary to the widely used concept of territorial or production-based accounting, which assigns emissions to the country in which they occur. Using multi-regional input-output systems based on national input-output tables and bilateral trade data makes it possible to estimate consumption-based emissions based on production-based emissions [19].

Influence of the diffusion of renewable power generation technologies on consumption-based emissions of the EU28 [19]



The figure shows the influence of the different factors on changes in consumption-based emissions in the EU28 countries as a whole. The year 2000 was selected as the baseline and compared with two scenarios. Scenario 1 estimates the consumption-based emissions for the final demand expected for 2020 using the technology forecast for 2020 (production structure and emission intensity for a greater diffusion of wind power and photovoltaics, see Boxes 5 and 6). Scenario 2 is based on the final demand in 2020 assuming the continued use of 2010 technology. While the stronger effect in scenario 2 with 2010 technology is that of the increase in final demand (and consumption-based emissions increase compared to 2000), in scenario 1, the effect of decreasing emission intensity is stronger due to the diffusion of wind power and photovoltaic which underlies the technology forecast for 2020, so that a drop in consumption-based emissions can be expected.

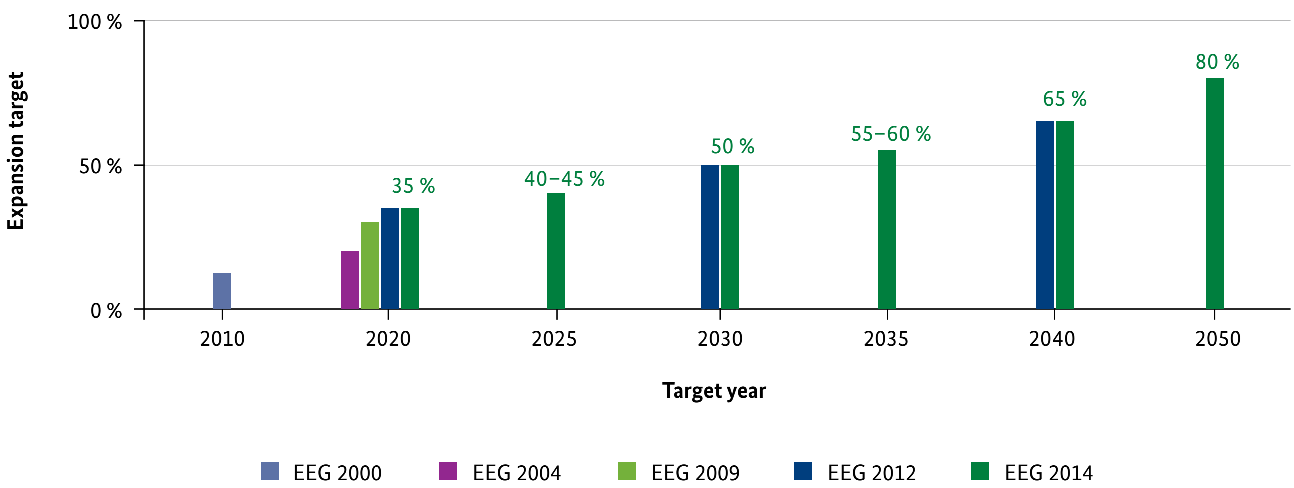
3 The policy mix for renewable power generation technologies

3.1 Objectives of the policy mix

The first German research and development programmes for renewable power generation technologies were launched at the time of the oil crises. From the 1990s, the development of renewable power generation technologies was also systematically promoted by the German Electricity Feed-In Act (StromEinspG), which was replaced by the German Renewable Energy Sources Act (EEG) in 2000. In 2010, the German government's Energy Concept resolved to transform the German energy system by 2050. Besides the 2011 decision to phase out nuclear energy by 2022, other main objectives are to cut greenhouse gas emissions by 80 percent to 95 percent by 2050 and to reduce energy consumption by 50 percent compared to 2008. The share of renewable energies in gross final energy consumption should increase from 12 percent in 2013 to 60 percent in 2050, whereas for electricity generation it is 80 percent.

The EEG contains specific targets for the share of gross electricity generation by renewables. These targets were sometimes exceeded in the past and have therefore been raised over time. For instance, the 2004 version of the EEG stated there should be a 20 percent share of renewable energies in German electricity generation by 2020. This was actually already achieved in 2011. As a reaction to this rapid expansion, the 2020 target was raised in the 2009 EEG and then again in the 2012 EEG revision (cp. Figure 12). A long-term, ambitious expansion target of 80 percent was embodied in the 2012 EEG, and the targeted expansion path was specified using corresponding interim targets in the 2014 EEG. The interim target for 2025 is regarded as ambitious by manufacturers of renewable power generation technologies according to the GRETCHEN survey (see Box 2 GRETCHEN survey 2014), but also as not ambitious enough given the 80 percent expansion target for 2050 [12]. However, the expansion target for renewable energies is part of a much more complex (energy) policy target system that encompasses economic development, social issues and other aspects such as nature conservation and species protection.

Figure 12: EEG expansion targets for the share of renewable energies in power generation [2]



3.2 Instruments and their interaction

A broad mix of instruments helps to achieve these targets. This mix is continuously enhanced over time and adapted to changes in the political and economic environment. The applied instruments encompass different fields of policy and have different goals. With regard to technological change, the instruments can be roughly grouped into three categories by their primary function: demand pull, technology push and systemic instruments. Figure 13 provides an overview of example instruments for these three categories and distinguishes them by type into economic instruments, regulations and information.

A mix of these instruments is used in Germany to promote renewable energies. This mix is made up of instruments from different fields of policy. For example, it includes instruments from energy and climate policy (e.g. EEG, EU ETS) and innovation policy (e.g. energy research programmes). But instruments from other policy fields are also relevant, e.g. environmental and biodiversity policy (e.g. the German Federal Nature Conservation Act). Figure 14 shows examples of the mix of instruments used over time in Germany.

The following section presents the most important economic instruments relevant for renewable power generation technologies in more detail.

Technology push instruments aim at supporting companies conducting R&D. This support usually takes the form of direct public funding of individual actors. The GRETCHEN survey indicates that around one quarter of the respondents received public funding in the years 2011-2013 (from Germany and the EU) for their R&D and innovation activities (see Box 2 GRETCHEN survey 2014) [12]. According to the funding database of the Federal Ministries, since the 1970s, €1,450 million and €383 million have been overall spent on R&D in photovoltaics and wind power, respectively. The individual research funding amounted to

Figure 13: GRETCHEN typology of instruments with selected examples [15]

Primary Type \ Primary Purpose	Technology push	Demand pull	Systemic
Economic instruments	RD&D* grants and loans, tax incentives, state equity assistance	Subsidies, feed-in-tariffs, trading systems, taxes, levies, deposit-refund-systems, public procurement, export credit guarantees	Tax and subsidy reforms, infrastructure provision, cooperative RD&D grants
Regulation	Patent law, intellectual property rights	Technology /performance standards, bans of products / practices, application constraints	Market design, grid access guarantee, priority feed-in, environmental liability law
Information	Professional training and qualification, entrepreneurship training, scientific workshops	Training in new technologies, rating and labelling programs, public information campaigns	Education system, thematic meetings, public debates, cooperative RD&D* programs, clusters

* RD&D = Research, development and demonstration

Figure 14: An excerpt showing the German instrument mix and its development (2000-2014) [14, 15]

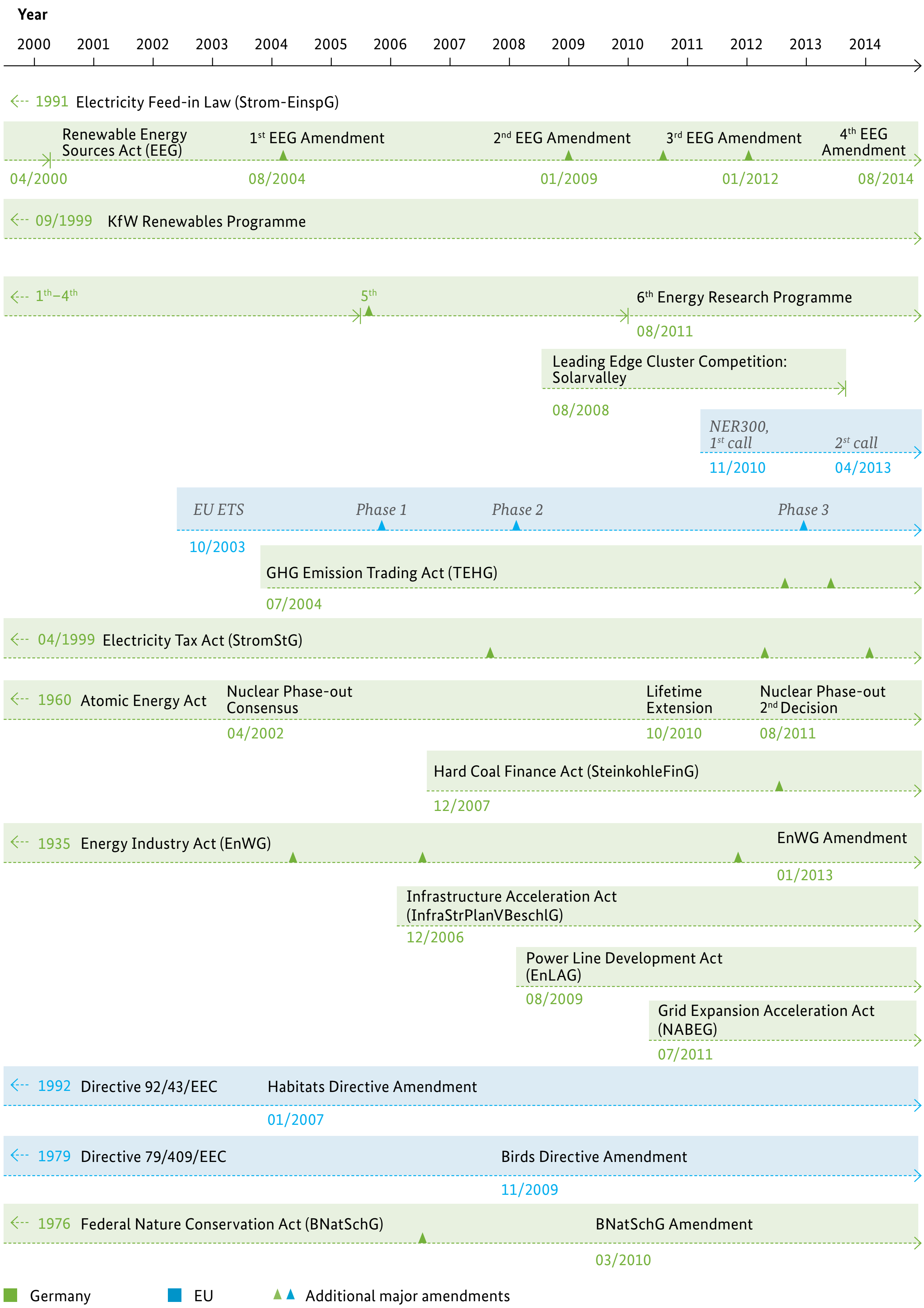
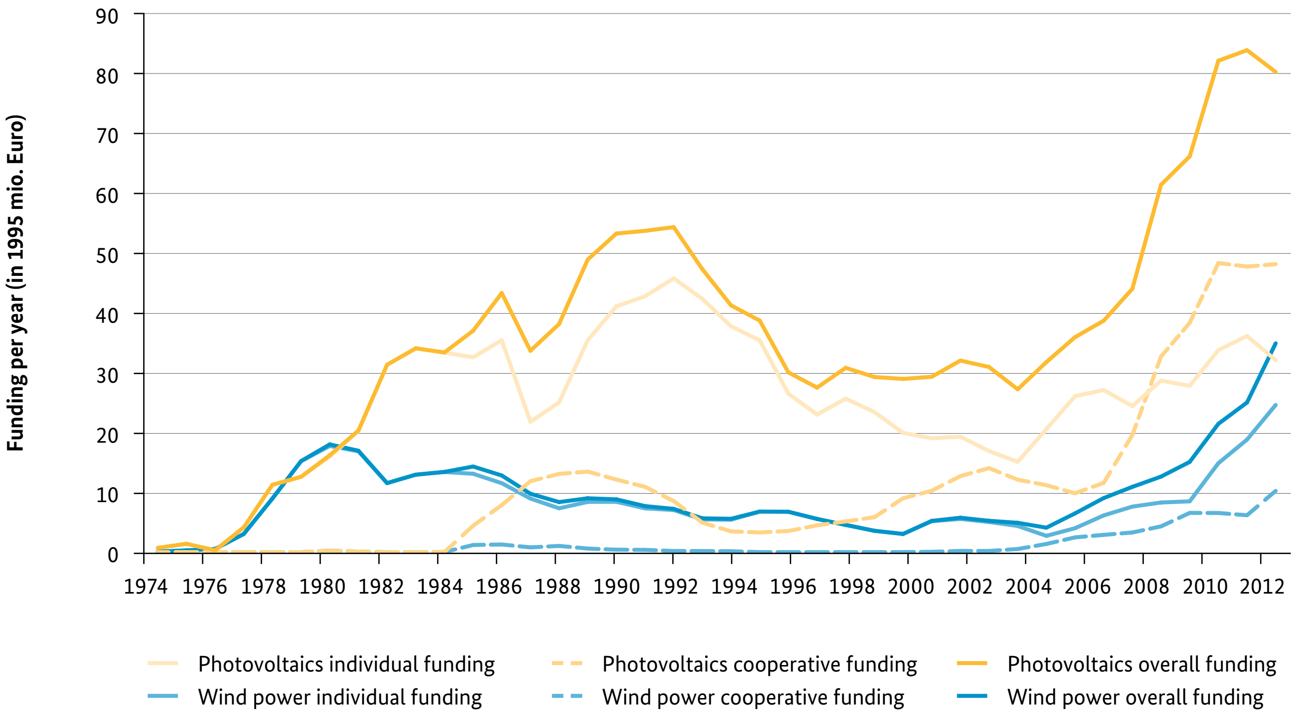


Figure 15: Public research funding of wind power and photovoltaics [4]



€1,010 million for photovoltaics and €331 million for wind power (all figures in 1995 prices) (cp. Figure 15) [4]:

- A strong upward trend is apparent for the public funding of photovoltaics from the end of the 1970s. This peaked in 1992 and then declined again in the subsequent period until it stabilised at around €20 million per year by the end of the 1990s. The annual funding starts to increase again from 2004 and reached €32 million in 2013. Since then, it has started to decrease again.

- There is a similar development for wind power, albeit with two significant differences: First, the overall level of annual funding is much lower than for photovoltaics, with the exception of a short period at the end of the 1970s. Second, the first funding peak appears much earlier – around 1980. This is followed by a longer phase of slowly decreasing funding that only ends in the year 2000. Funding then increased continuously again to about €25 million in 2013.

Systemic instruments modify and improve the general framework conditions for actors and enhance or facilitate innovation activities in this way. Such improvements are usually aimed at the (research) infrastructure and include, for example, promoting the training of skilled workers. The GRETCHEN survey indicates that this has a similarly strong influence on supporting the expansion of renewable power generation as public R&D support and the EEG [12]. In addition, systemic instruments aim to improve the exchange of knowledge and information among actors. In Germany, for example, collaborative research or clusters are supported (such as the Solar Valley) which specifically target cooperative R&D projects of different actors (e.g. businesses and research institutions). Since the 1970s, funding of €440 million has been allocated to cooperative research on photovoltaics and €52 million to wind power (cp. Figure 15) [4]:

- Cooperative research accounts for a relatively large share of total funding in photovoltaics and recently even exceeded the share of individual grants. It amounted to €48 million in 2013.

- The share of cooperative research in wind power was very low for a long time and did not even exist at all in the mid-1990s. However, it increased continuously from 2003 to a level of €10 million in 2013.

Demand pull instruments support technology development indirectly by spurring market growth. Policy measures such as the 100/250 MW programme for wind power and the 1,000/100,000 roofs programme for photovoltaics were used in the 1990s to try and develop limited niche markets. These programmes were flanked by the Electricity Feed-In Act of 1991 that introduced a purchase guarantee for electricity produced from renewable energies and technology-independent remuneration for the electricity fed into the grid. However, because this was not enough to compensate the higher production costs of the majority of renewable energies compared to fossil sources, in 2000, the EEG was introduced with significantly higher and technology-specific feed-in tariffs. The explosive market development triggered as a result – especially in photovoltaics – can be largely explained by the effect on the **profit margin** (see Box 8 Profit margin). Alongside the domestic market, the results of the GRETCHEN survey confirmed that foreign countries' policies towards market creation and/or growth are now also increasingly relevant [12].

Box 8 Profit margin

The profit margin shows the "pull" effect of the instruments promoting demand. It integrates the effect of the different demand pull instruments (feed-in tariffs, interest subsidies, investment grants) on the cash-flow of investment. The profit margin can therefore be seen as the operationalised policy variable for the mix of demand pull instruments that was calculated in GRETCHEN for photovoltaics and for wind power as: profit margin = feed-in tariff – levelized costs of electricity generation (LCOE) + annuity of financial support.

The margin was determined with and without funding for photovoltaics (cp. Figure). The margin with and without funding increases over time in line with the cost development. Demand pull instruments result in a much greater margin. However, in the last year under review, the margin without funding is higher than that with funding because the feed-in tariff is below the household price for purchasing electricity (reference case without funding) [1, 2, 3].

Development of the profit margin for photovoltaics (10-kWp systems) with and without funding [2]

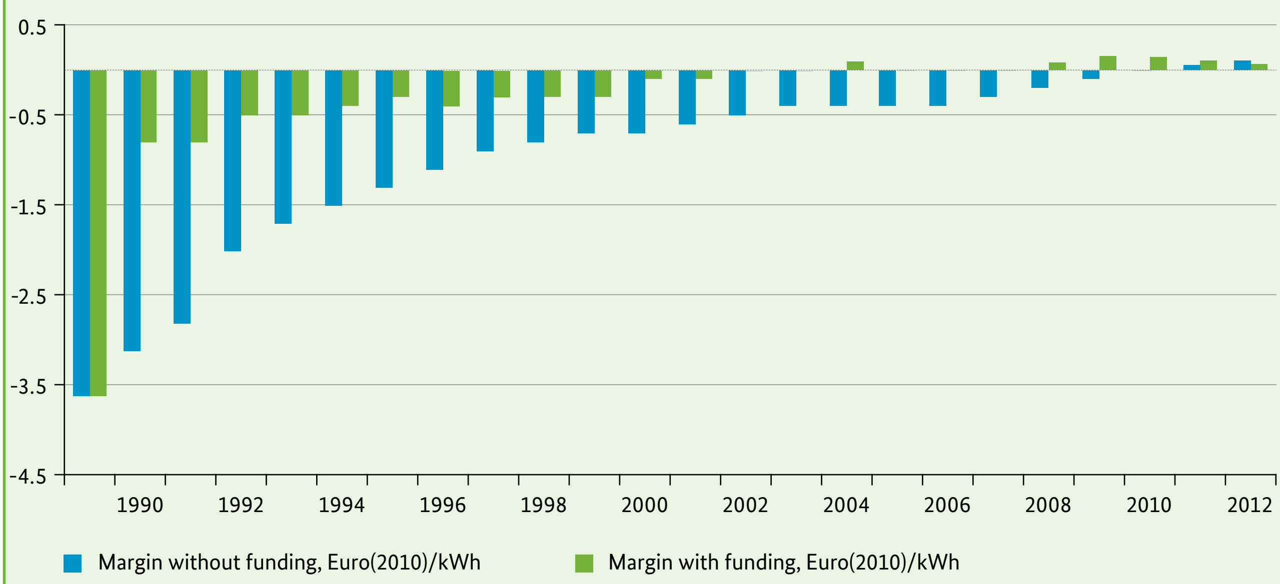
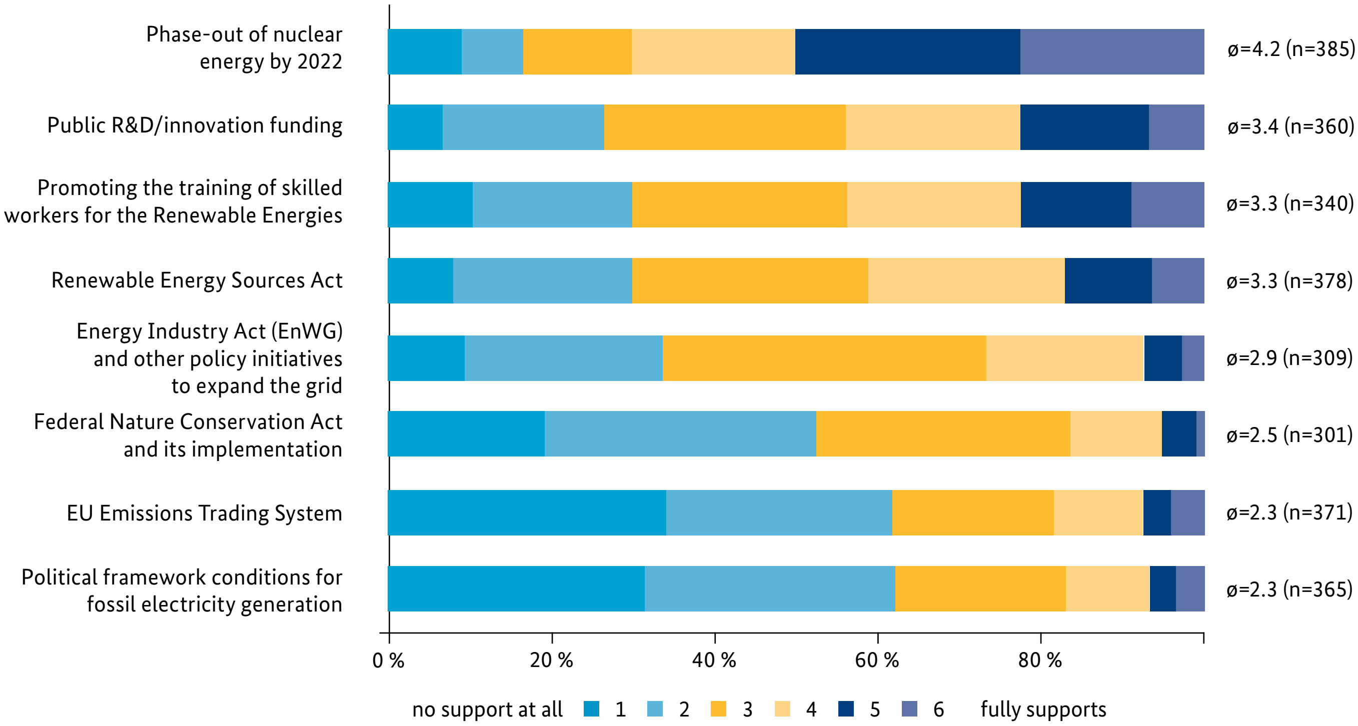


Figure 16: Assessing the supportive effect of selected instruments [12]

Please state how much you think these political instruments and measures support the expansion of renewable electricity generation in their current form?



These individual instruments do not exist in isolation, but together constitute an **instrument mix**. Within the GRETCHEN project, it was therefore also examined whether the interaction of instruments in the mix has an effect that goes beyond the effect of single instruments. For example, it can be assumed that demand pull and technology push instruments mutually reinforce each other, since the former raises the number of actors potentially able to do R&D, while the latter improves their capability to do so. However, the GRETCHEN survey indicates that the recent proposals to shift EEG funds in the direction of more support for R&D are viewed rather critically [12].

The composition of this instrument mix has changed considerably over time and supporting measures have been added that address the many technological, societal and ecological challenges involved (cp. Figure 16). Despite this, according to the GRETCHEN survey, more than two thirds of the companies in 2014 complained about the lack of important accompanying policy instruments needed to support the expansion of renewable energies [12].

While, for example, German-based manufacturers believe the nuclear phase-out offers the strongest support for developing renewable energies, the EU Emissions Trading System hardly seems to have any effect (cp. Figure 16). The same holds for the framework conditions for fossil power generation technologies that are currently not specifically designed to support the expansion of renewable energies. Overall, the companies perceive only limited synergies among the existing instruments [12].

3.3 Credibility and coherence of the policy mix

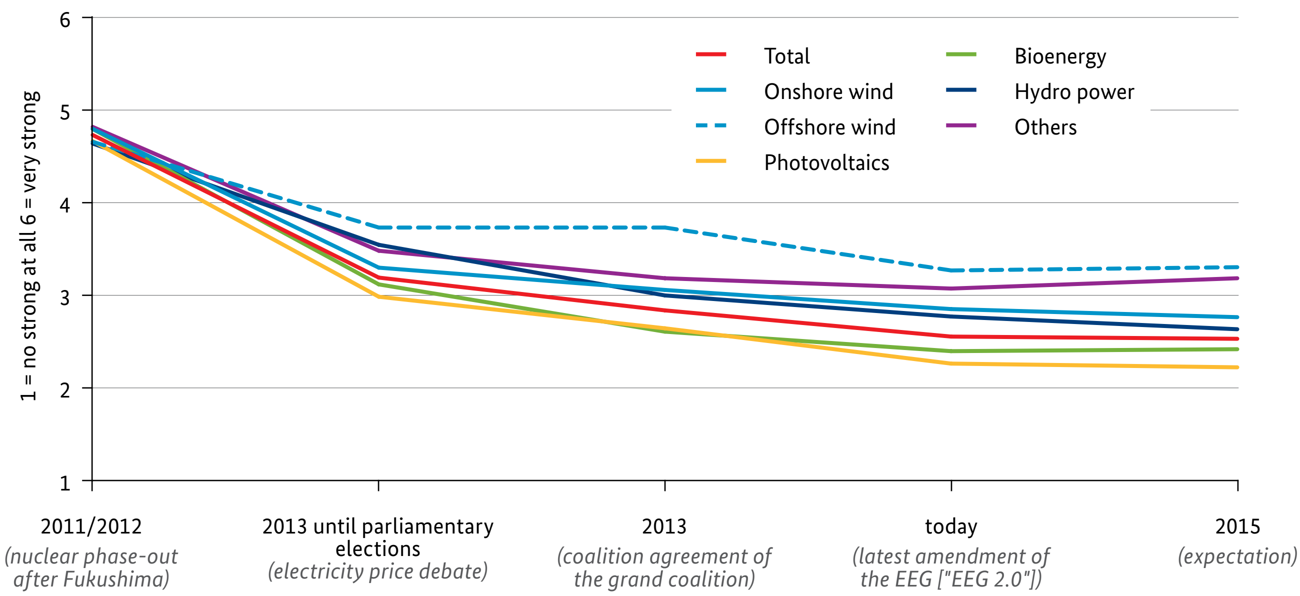
According to the GRETCHEN survey, the manufacturers were most keenly aware of the **political will to promote power generation from renewable energies** at the time of the nuclear phase-out after Fukushima (see Box 2 GRETCHEN survey 2014). As Figure 17 shows, however, companies think this political will has ebbed away since then [12]. The strongest drop occurred during the electricity price debate initiated by the then Federal Environment Minister, Peter Altmaier: In order to limit the rising costs caused by the EEG surcharge, he suggested cutting the guaranteed feed-in tariff retroactively. This suggestion – that was later retracted – triggered considerable uncertainty among investors because it threw doubts, for the first time, on the high predictability and associated investment security of Germany's core demand pull instrument. Although, in the end, the EEG's design was not modified, the perceived strength of the government's commitment to promote renewable power generation has still not recovered since this debate. Indeed, it continued to drop after the elections and only began to stabilise in 2014/15, i.e. after the 2014 EEG was enacted, albeit at a relatively low level [12, 13].

If the companies' perceptions of the German government's commitment are distinguished by technologies, it can be shown that the political will to expand renewable energies was perceived as similar across all technologies in the period 2011/12 but has been differentiated since then [12]. For instance, offshore wind companies perceived political commitment to be the strongest in 2014 [see also 9, 10, 11]. In comparison, PV and bio-energy companies have the lowest perception of the political commitment [12]. This might be due to the strong reduction of feed-in tariffs and the limits on the potential for market growth due to the introduction of narrower expansion corridors.

The GRETCHEN survey included questions about the **credibility** of the policy mix for 2014 using different formulations. Companies perceive a cross-party consensus to expand power generation from renewable energies and feel there is a relatively high level of societal acceptance and support from local and Federal State governments. What they are missing is a stable political commitment and clear political vision concerning the increase of power generation from renewable energies [12]. Companies distinguish clearly between credibility on a national level (and thus the political commitment of the federal government) and sub-national level (the political commitment of local and regional authorities) [13, 16].

Figure 17: Development of manufacturers' perception of the German government's commitment to promoting renewable power generation (2011-2015) [12]

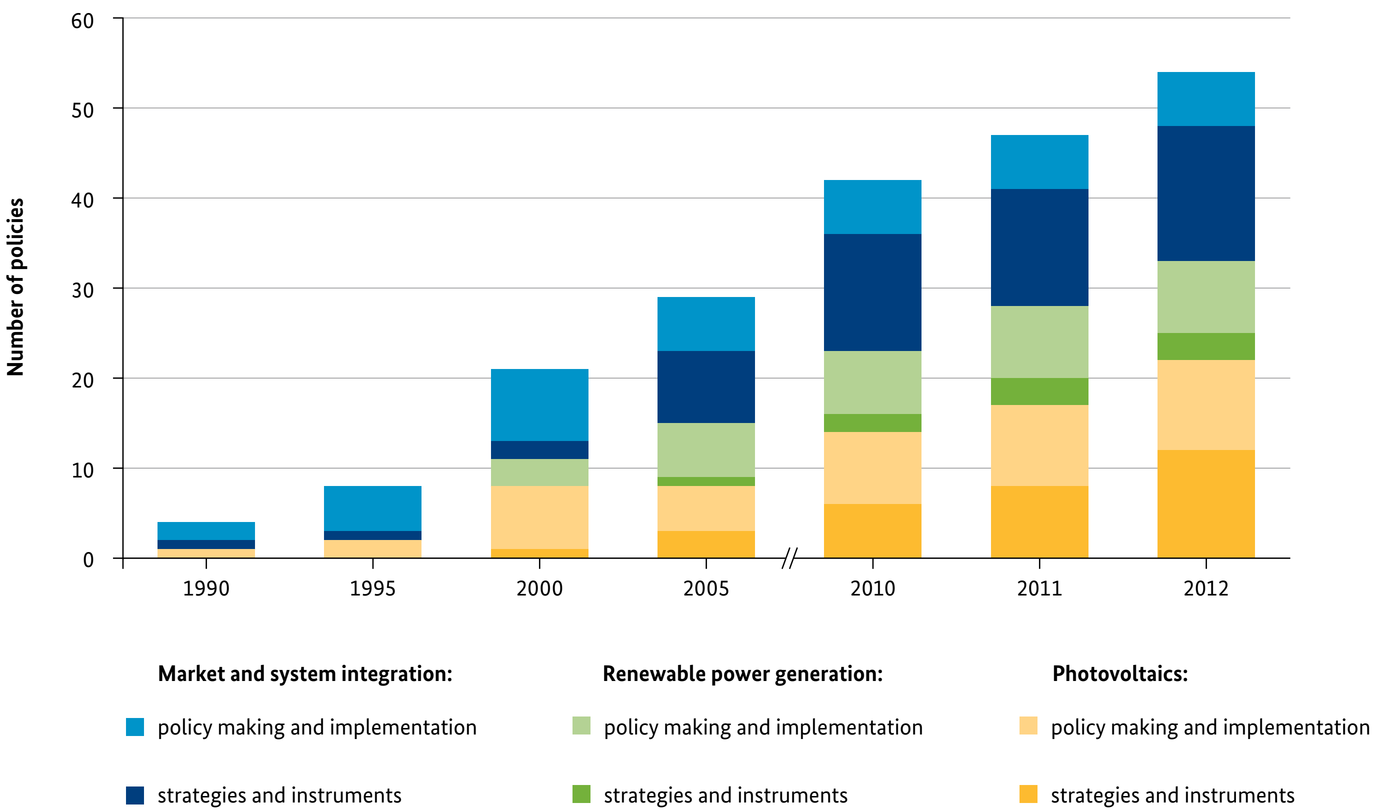
How strong do you think the political will was/is of the respective German government at the following points in time regarding the promotion of renewable electricity generation?



These results indicate that the steady **increase in the number of policy measures** – as shown in Figure 18 for photovoltaics – may not necessarily be understood by companies as an indication of strong political commitment. Instead, it is possible that high political activity is only perceived as political commitment to a technology if the instruments and their implementation are specifically designed to be advantageous for the manufacturers of the respective technologies. This seems to be the case since the end of 2012, especially for photovoltaics. The decrease in the feed-in tariffs together with the pressure from global competition has resulted in a drop in sales for German producers. This slump could have had a negative impact on the manufacturers' viewpoint and probably played a role in their perception of the lack of political commitment to promoting renewable energies. However, the increase in the number of policy instruments that target the market and system integration of renewable energies and the implementation of the expansion strategy could also be interpreted as policy makers' continued commitment to further push expansion [2].

The GRETCHEN survey indicates a relatively low **coherence of the political processes** for deciding upon and implementing the policy mix for renewable power generation technologies. The biggest complaints of Germany-based manufacturers are that problems in the industry are not recognised early enough by policy makers and that obstacles are not always removed. In addition, there do not seem to be many constructive dialogues between policy makers and manufacturers when addressing problems. Furthermore, the most recent EEG amendments do not seem to have been transparent enough [12]. Studies of offshore wind power, for example, on increasing the feed-in tariffs in the 2012 EEG show that the manner in which such political problem-solving processes are conducted can influence how well the technological innovation system functions [9, 11]. Finally, companies stated that the responsibilities could be more clearly defined in the relevant federal ministries. Moreover, regional and national authorities do not always seem to be moving coherently in the same direction [12].

Figure 18: Number of policy measures related to photovoltaics (1990–2012) [2]



4 Impact of the policy mix on innovation

This section examines the effect of the policy mix presented in the previous chapter on the development of the market and especially on the development of the technologies described in Chapter 2. This explicitly considers the multi-layered nature of technological change using different indicators – such as patent output, private R&D expenditure, tendency to cooperate or the degree to which research is embedded in the international context.

4.1 Impact of targets and their consistency on innovation

In the GRETCHEN survey, manufacturers of renewable power generation technologies stated that the 2025 **expansion targets for renewable energies** were the second most important political factor influencing their innovation activities in the period 2011-2013 (see Box 2 GRETCHEN survey 2014). The companies considered Germany's expansion targets to be similarly influential to demand pull instruments at home and abroad and the government's commitment to *Energiewende* to be credible [12]. However, the specific level of companies' R&D spending cannot be explained by the 2025 expansion target for renewable energies. The same thing applies to the perceived consistency of the government's various energy and climate policy targets. However, the results do suggest that manufacturers, who believe the medium-term expansion target for 2025 is not ambitious enough in light of the 80 percent target for 2050, spend comparatively less on innovation [16]. This effect could be due to the fact that companies do not consider the 80 percent target credible based on the planned course of expansion.

Case studies of German manufacturers and operators of offshore wind power installations show that the technology-specific **offshore wind power strategy** of 2002 – that was stable and consistent over a period of ten years and featured long- and medium-term targets – had a major influence on companies' innovation activities. Besides this, the consistency of the overarching policy mix also played a key role for corporate R&D activities. The incentive to innovate came not only from the ambitious offshore wind power expansion targets, but also crucially from the fact that these were actually implemented with the appropriate instruments [9].

One result of the macroeconomic modelling is that decarbonising electricity generation ultimately makes an important contribution to achieving the German government's ambitious **climate targets** [21]. However, this is not enough on its own – it is essential to continue to improve energy efficiency in every industry, and more CO_2-free options have to be used, especially in heat supply and transport. Here, it is important to consider the climate effects of technologies across the entire life cycle and take indirect emissions into account as well. In electric mobility, for instance, the effect on total emissions depends heavily on whether the additionally required electricity is supplied by renewable power generation technologies.

4.2 Impact of individual instruments and their interaction on innovation

As part of the GRETCHEN project, the innovation impact of a series of policy instruments was analysed in more detail. The next paragraphs look at the effects of technology push, systemic and demand pull instruments separately (especially in Germany, but also abroad) and subsequently the effect of the instrument mix is considered.

Technology push instruments have positive effects on technology development – on patent applications [1, 4], private R&D expenditure [16], the size of the national innovation system and its interconnectedness [4], and the access to international knowledge [5] – as well as on technological competitiveness to some extent [3].

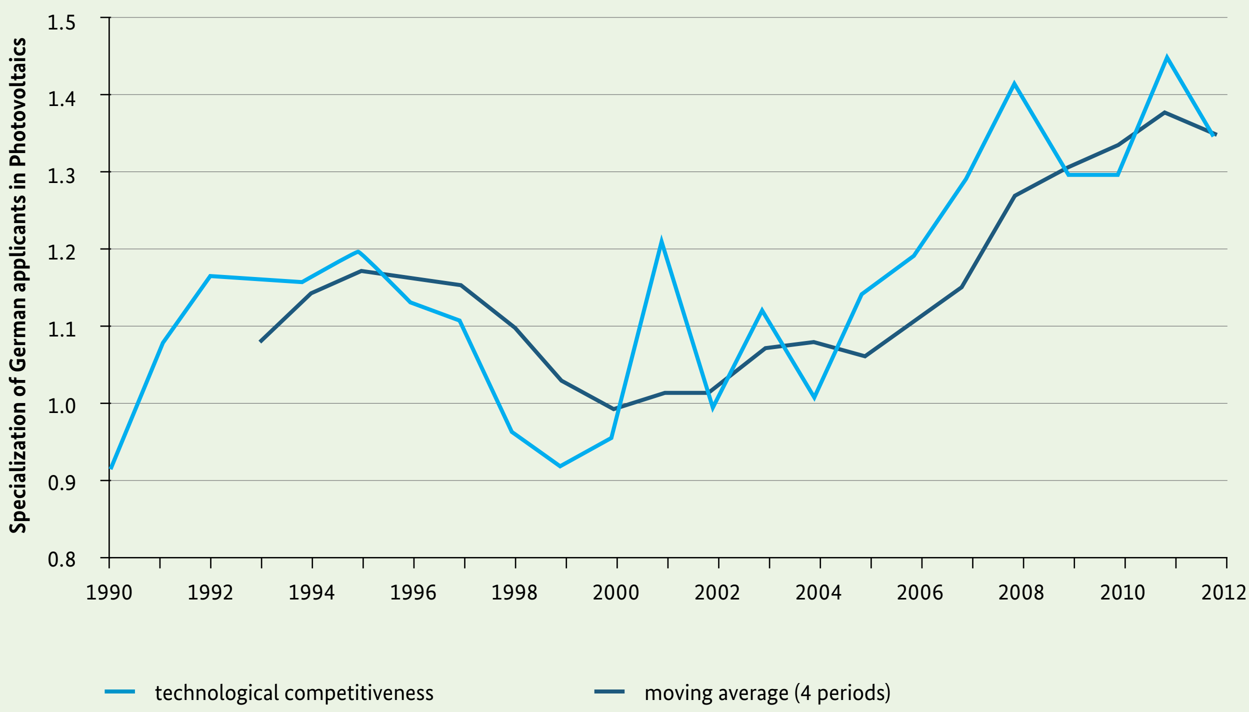
The results confirm a positive link between public research support and patent applications of German inventors in photovoltaics and wind power [1]. Analyses of the GRETCHEN survey also indicate that manufacturers of renewable power generation technologies tend to spend more on R&D if they had previously received public funding from Germany and/or the EU to conduct R&D projects (see Box 2 GRETCHEN survey 2014) [16]. In addition, technology push instruments increase the number of patenting actors, especially in wind power. In photovoltaics, in contrast, they result in a greater interconnectedness of the actors [4]. The quality of international publication partners is also positively influenced, which indicates that supported actors are attractive partners for cooperation. However, the effect on the number of links to other countries is slightly negative [5].

A different picture emerges for the influence of technology push instruments on technological competitiveness (see Box 9 Technological competitiveness). There is a limited effect of this individual instrument for photovoltaics. If, in contrast, the joint effect of technology push instruments and expansion targets is examined, there is a clear influence of this target-instrument combination on the technological competitiveness of the German photovoltaics industry [3].

Box 9 Technological competitiveness

The technological competitiveness shows how strongly German patent applicants have specialized in photovoltaics in comparison to the rest of the world. The calculated ratio is that of photovoltaic patent applications to total patent applications of German applicants in comparison to global photovoltaic patent applications to total global patent applications. A value over one indicates a stronger orientation of German applicants towards photovoltaics than the rest of the world and thus a good position for future markets. The development of the technological competitiveness in the figure shows an overall strong position of the German photovoltaic technology providers [2].

Development of the technological competitiveness of photovoltaics in Germany [2]



Systemic instruments prove to be particularly effective for promoting knowledge exchange via patent cooperations [4] and international embeddedness [5]. Looking at knowledge exchange through patent cooperations in the German innovation system reveals positive effects for photovoltaics and wind power, and, regarding the number of patents, the number of researchers and their degree of interconnectedness. The effect of systemic instruments seems to be much stronger on wind power networks than on photovoltaics [4]. If publications are used to analyse the degree of networking and international embeddedness of photovoltaics research, it is clear that the skilful design of domestic research systems can positively influence international embeddedness and thus the access to external knowledge. For example, a large number of interconnected actors in a national research system is more beneficial to international knowledge exchange than the focus on only a few national champions [5].

Demand pull instruments usually lay the foundation for the formation of an attractive market and have strong positive effects on technological change – measured using patent applications [1, 4], private innovation activities and R&D expenditure [12, 16], the extent and degree of networking in the national innovation system [4] and the access to international knowledge [5] (see Box 10 Operationalisation of the demand pull instruments). There is also a positive influence on technological competitiveness [3].

It is apparent that increasing market demand – and the related production capacities – has a strong, positive effect on the number of **patent applications** for photovoltaics and wind power [1, 4]. The GRETCHEN survey also clearly shows that policy-driven market demand has a positive influence on innovation activities for the manufacturers of renewable power generation technologies. The existing and expected domestic and foreign demand pull instruments play a key role here among the political factors influencing companies' innovation activities [12]. If these instruments indicate an expected increase in sales, then companies increase their **innovation expenditure** [16].

There is also a positive influence on **cooperation** of promoting demand. The number of patenting inventors and their interconnectedness increases strongly in the field of photovoltaics, while there only seems to be a weak positive influence on wind power [4]. Domestic expansion and government procurement, for example, the demand for specialized, high performance photovoltaics cells for satellites, also play a role for the degree of embeddedness in the international photovoltaics research landscape [5].

Box 10 Operationalisation of demand pull instruments

A large number of different demand pull instruments were used to create a niche market for renewable energies. Four approaches were employed to quantify them in GRETCHEN:

- **Annual expansion of the individual renewable power generation technologies** [1, 4, 5]: corresponds to the market demand – this can largely be traced back to demand pull instruments in the past, because the technologies were not competitive without funding (analysis can be limited to additional domestic capacity or include the markets in other countries);
- **State procurement of specialized solutions** [5]: in this case the number of satellites, which are usually powered using particularly powerful photovoltaic cells;
- **Profit margin** [1, 2]: the margin that investors in renewable power generation technologies can achieve and that usually only becomes positive due to demand pull instruments; and
- **GRETCHEN survey** [12, 13, 16]: manufacturers of renewable power generation technologies were asked direct questions about the effect of demand pull instruments.

The **design features**, i.e. how the demand pull instruments are designed, also also influences innovation activity. For instance, the GRETCHEN survey indicates that the amount and guaranteed duration of the feed-in tariffs, but also their annual degression, influence companies' innovation activities [12]. In the case of wind power, for example, the gradual reduction of the feed-in tariff seems to be accompanied by increased innovation activities. One reason for this might be the contribution to the reduction of the levelized costs of electricity generation and the enlargement of sales markets [1, 12].

Other analyses of photovoltaics within GRETCHEN show that demand pull instruments can have a clear positive influence on **technological competitiveness** through their effect on the market. This is probably due to the increase in competition, the realization of economies of scale accompanying demand pull measures and the further development of technologies and production processes. All these factors contribute to declining technology costs [2, 3].

The influence of the **international expansion** of renewable power generation technologies (and therefore of the policy mix of other countries) on the German market was estimated using modelling simulations conducted with GINFORS_E (see Box 6 Endogenisation of technological change in the GINFORS_E model). Especially in the field of photovoltaics, it becomes clear that it is very difficult to match the incentive effect of demand pull instruments to be in line with targets. In the years from 2009 to 2013, for example, the feed-in tariff for photovoltaic installations was not decreased quickly enough, so that expansion in Germany far exceeded the targeted corridor. One reason for the too slow reaction is international learning curve effects that lower the costs of photovoltaics much faster than could be expected from a purely national perspective. Not considering the international perspective led to overachieving the target [21]. **Projections** into the future show that it is difficult to find the optimum feed-in tariff level for photovoltaics, also because it is so hard to predict future policy measures in other countries. This problem is less pronounced for wind power since the technology is already more mature and the learning curve effects are therefore smaller [19, 21].

When **analysing the instrument mix**, it becomes clear that there is a positive joint effect of demand pull and technology push instruments for wind power and photovoltaics on the number of patents and inventors. A similar relationship can be observed for the interaction of systemic and demand pull instruments regarding the interconnectedness of actors in both technologies. Additionally, technology push and systemic instruments seem to only function properly as intended if demand pull instruments are applied at the same time. Demand pull instruments therefore represent an important necessary prerequisite to effectively support innovation and a well-functioning innovation system [4]. Furthermore, the results of the GRETCHEN survey indicate that manufacturers spend more on innovation if the different instruments mutually reinforce each other. If, on the other hand, there are inconsistencies in the mix of instruments, companies seem to be more careful with their innovation expenditure [16].

To sum up, it can be concluded that technology push and systemic instruments and the instruments used to create demand for renewable power generation technologies had a positive and mutually reinforcing effect on innovative activity. It is therefore not advisable to back only one instrument when promoting innovation. Instead, a mix of instruments is needed that includes instruments with different functions that complement each other's effect and therefore in combination have a stronger positive impact on technological change.

4.3 Impact of the consistency, credibility and coherence of the policy mix on innovation

So far, the analyses studied the innovation effect of targets (Chapter 4.1), instruments and the mix of instruments (Chapter 4.2) separately. This chapter now goes one step further and examines whether the characteristics of the policy mix (consistency, credibility and coherence) also influence innovation.

Regarding the **consistency of the policy mix**, a majority of the manufacturers of renewable power generation technologies in the GRETCHEN survey said that the existing political instruments will not be able to meet the ambitious 2025 German expansion targets for renewable energies (see Box 2 GRETCHEN survey 2014). The perceived discrepancy between instrument mix and targets seems to have a major influence on the amount companies spend on innovation: Companies that regard the instrument mix as not ambitious enough to achieve the targets invest less in innovation activities. In addition, the match between instruments and targets becomes more relevant for corporate innovation expenditure if the perceived credibility of the policy mix is also taken into account [16]. For offshore wind power, it was further determined that the negative innovation impact of an inconsistent policy mix can be compensated at least partially by a high credibility of the policy mix [9].

Furthermore, the results of the GRETCHEN survey show that a credible commitment of policy makers to the *Energiewende* played an important role for the innovation activities of manufacturers of renewable power generation technologies in the period 2011-2013. This **credibility** of the policy mix was regarded by companies as almost as important a factor for determining their innovation activities as the German Renewable Energy Sources Act (EEG), the political expansion targets and foreign demand pull instruments, whereas the EU Emissions Trading System played hardly any role [12]. More detailed analyses indicate that those companies which view the policy mix as more credible invest more in R&D and vice versa. These indications of the decisive role credibility plays for private innovation expenditure are reinforced if the consistency of the whole policy mix is considered as well [16]. The significance of credibility is also underlined by the fact that companies that did not conduct any innovative activities in 2011-2013 cited the lack of a credible commitment of policy makers to the *Energiewende* as the most important political reason for not doing so [12].

Excursus: Tracing the determinants of credibility [13]

The GRETCHEN survey of Germany-based manufacturers shows the high relevance of the policy mix's credibility for green technological change. This leads to the question of which aspects of the policy mix influence this credibility.

- **Policy strategy:** If the long-term expansion target for the share of renewable energies in power generation in 2025 is regarded as relatively ambitious, then the perceived credibility is also higher.
- **Instrument mix:** Not only the EEG and the associated promised support for expanding renewable energies has a positive influence on the perceived credibility. Companies' perceptions of the support for the expansion of renewable energies from the nuclear phase-out, the regulations for expanding the grid and the EU Emissions Trading System also determine the perceived credibility of the policy mix.
- **EEG design:** If a closer examination is made of the changes to the EEG in 2014, then the decline in feed-in tariffs and the introduction of technology-specific expansion corridors have had a negative impact on the perceived credibility of the policy mix.
- **Consistency of the policy mix:** The perceived credibility is influenced even more strongly by how well the targets of energy and climate policy are coordinated, how well aligned the instruments are and to what extent the mix of instruments is regarded as sufficient to achieve the long-term goals.
- **Coherence of the political processes:** A higher credibility rating of the policy mix is correlated with more positive assessments of the flow of information between businesses and political decision-makers and the speed of identifying problems and solving them.

There seem to be many different ways to improve credibility – and therefore increase corporate spending on innovation in renewable power generation technologies: Targets can be set more ambitiously, or the individual elements of the policy mix can be better coordinated. In concrete terms, for example, "repairing" the EU ETS would aid credibility. Improving the information flow between businesses and policy makers and optimizing policy design processes would also probably help to increase the credibility of the policy mix.

There is only limited proof that the **coherence** of the political decision-making processes has a direct influence on innovation. However, there are some indications that especially procedural aspects, for instance the processes of amending the EEG that were perceived as not sufficiently transparent or the partially contradictory signals given by national and federal governments, could have had some influence on the amount companies invest in R&D [16]. Furthermore, in the case of the electricity price debate, interviews with manufacturers of and investors in offshore wind power installations showed that political debates can indeed have a direct influence on innovation – in the case mentioned, a negative influence, because of the resulting loss of confidence [9].

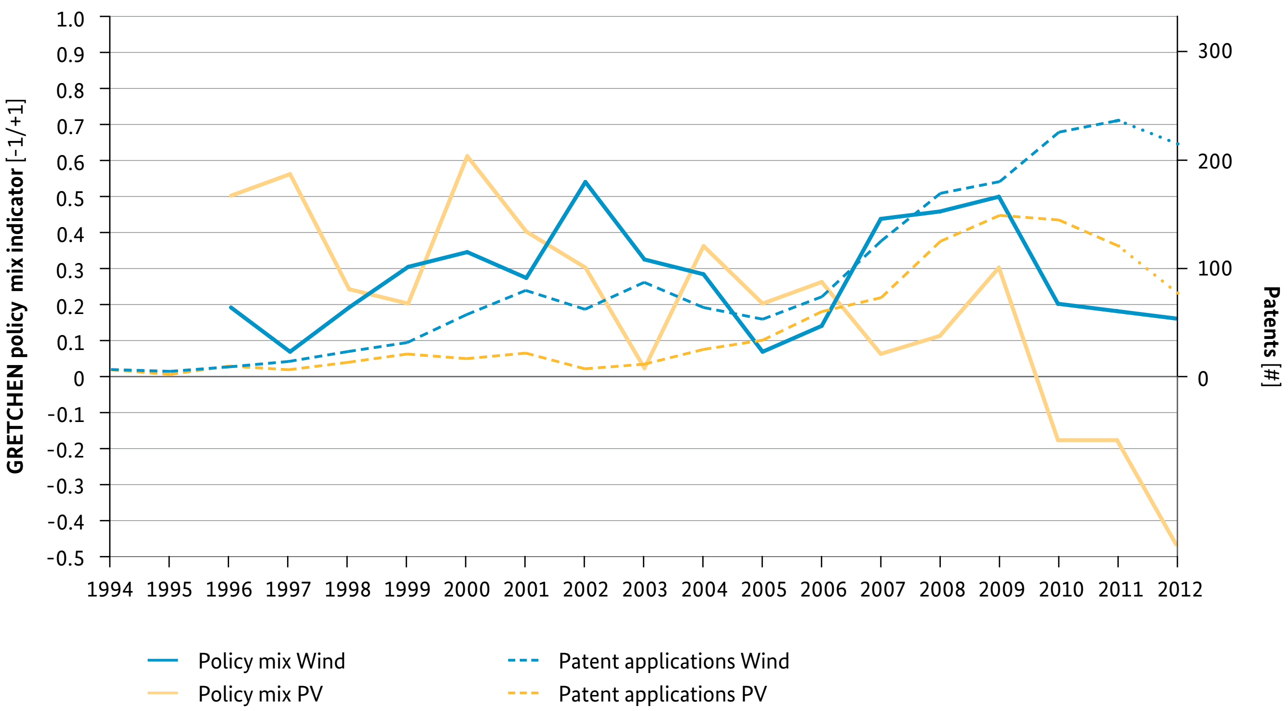
4.4 Impact of the overall policy mix on innovation

The analyses conducted in GRETCHEN showed that the policy mix for renewable energies clearly has an effect on technological change in renewable power generation technologies. However, the studies conducted so far have only highlighted partial aspects of the policy mix concept presented in Chapter 1. Within the GRETCHEN project, therefore, first attempts were made to analyse the effect of the policy mix as a whole on technological change.

To do so, an indicator was constructed for the policy mix for photovoltaics and wind power, which combines the different components of the policy mix concept (see Box 11 **GRETCHEN policy mix indicator**). There are clear indications that plotting this policy mix indicator helps to explain technological change in Germany – measured using the patent applications of German inventors. The results are again distinguished into photovoltaics and wind power [1]:

- For **photovoltaics**, the analyses indicate a negative correlation between the measured attractiveness of the policy mix as a whole and patent applications. That is, patent applications increased in the past despite the slow decline in the attractiveness of the policy mix. However, a reversal of this trend seems imminent after the policy mix indicator falls below zero which coincides with patent applications having slumped significantly since then. This is a prominent trend break because until then annual patent applications had risen continuously.
- For **wind power**, in contrast, the analyses indicate a positive correlation of the GRETCHEN policy mix indicator and patent applications. In other words, the number of patent applications follows the perceived attractiveness of the policy mix for wind power. This close correlation is already apparent in the almost parallel development of patent applications and the policy mix indicator in Figure 19. Accordingly, this suggests that the wind power patent applications made in 2012 will have continued to decrease, something the most recent patent figures seem to confirm.

Figure 19: Development of the GRETCHEN policy mix indicator and patent applications of German inventors for photovoltaics and wind power in the period 1994–2012 [1]



Box 11 GRETCHEN policy mix indicator

In order to capture the dynamics and complexity of the policy mix, an aggregated policy mix indicator was developed as part of the GRETCHEN project – for photovoltaics and wind power separately. The monthly specialist journals "Photon – Das Solarstrom-Magazin" (1996-2012) and "Wind Power Monthly" (1994-2012) were searched for articles reporting on developments in the policy mix. Based on analysing the content of 1,063 articles for photovoltaics and 801 articles for wind power, a policy mix database was compiled that records each development in the policy mix. Not only the specific design of policy instruments plays a role, but also discussions about their implementation and modifications as well as foreign policy measures. All these kinds of documented "policy mix events" were then evaluated with '+1' (or '-1') if the policy mix development was perceived as positive (or negative) for the technology, and with '0' if the article assumed that the development was neutral for the technology. An annual policy mix indicator was then calculated from these results that reflects the perceived attractiveness of the policy mix for a technology. To do so, first, all the individual evaluations of one year were summed up and then divided by the number of policy mix events so that the indicator takes on an annual value ranging from '-1' to '+1'. At a glance, this indicator then shows how the attractiveness of the technology-specific policy mix is estimated to have developed over the last twenty years.

According to this, the attractiveness of the policy mix for photovoltaics and wind power was largely positive in the past, although subject to fluctuations. In addition, the development of the indicator varied clearly between photovoltaics and wind power (cp. Figure 19):

- For **photovoltaics**, the GRETCHEN policy mix indicator reveals that the general tendency is that the attractiveness of the policy mix has decreased over the last 20 years and even became negative from 2010. The intensive discussions about the future of photovoltaics support and unscheduled reductions in the feed-in tariff as well as the plans to restrict the expansion of photovoltaics probably contributed significantly to this development. These negative developments are captured much less clearly or not at all when considering other indicators – such as the profit margin or the annual development figures.

- The policy mix indicator also fluctuates for **wind power** over time, but never becomes negative during the period under review. To start with, the attractiveness of the policy mix increases until 2002, followed by a slump that reaches its lowest point in 2005. After recovering in the following years, the indicator almost re-achieves its 2002 maximum in 2009, but then drops again, although less dramatically than the GRETCHEN policy mix indicator for photovoltaics [1].

Overall, it can be concluded that an overarching policy mix indicator can be a useful supplement when monitoring the *Energiewende* because it offers a quick, first impression of developments in the policy mix. Due to its combined consideration of targets, instruments and especially political debates and softer factors, this GRETCHEN indicator is able to map changes in the policy mix that would otherwise be difficult to measure. At the same time, the most recent, drastic and negative changes in the perception of the policy mix for photovoltaics, which are revealed by the GRETCHEN indicator and which are associated with a decline in patent activity, underline the importance of a broader understanding of the policy mix.

5 Policy and research implications

The GRETCHEN project has generated many insights into how the policy mix affects innovation in renewable power generation technologies, but has also revealed some knowledge gaps. The following recommendations can be drawn for policy making and research.

5.1 Policy implications

An intensive political debate about the promotion of renewable energies has taken place over the last few years in Germany. To some extent, this debate has been constricted too narrowly to the EEG. The results of the GRETCHEN research, in comparison, highlight that all the aspects of the policy mix have promoted the development and diffusion of these technologies in Germany. Three general policy recommendations can be derived from this for tackling the future political challenges when transforming the energy system:

- To successfully shape technological change in the energy system, it is essential to have a carefully coordinated combination of different policy instruments. The **policy mix** has to be understood and designed **as a whole** – backing only one instrument will not achieve the desired result.

- In order to stimulate dynamic innovative activity, this policy mix has to be **credible** and internally **consistent** to the greatest possible extent. Without a strong political will for green change, there is uncertainty about future market developments which hinders long-term investments in innovation and threatens Germany's technological competitiveness in the analysed technologies.

- The shift towards renewable power generation technologies is an increasingly global process that will need much **greater supranational coordination** of the policy mix in the future. The discussion about the *Energiewende* in Germany should be specifically orientated towards its **benefits** – in the form of export opportunities, jobs and its contribution to international climate protection and sustainable development, among other things.

These three main policy recommendations concerning a supranationally-oriented, consistent and credible policy mix and a political debate that places more emphasis on the benefits of the *Energiewende* are derived from the following specific results of the GRETCHEN project:

One of the key aspects is that the **mix of instruments** used to promote renewable energies has different effects depending on the technology and the phase of the innovation process. Also, demand pull measures, technology push and systemic instruments support each other. Applying a mix of instruments must therefore consider the different phases of the innovation process and ensure coverage of the different target groups involved in each phase such as technology developers, manufacturers and consumers.

- **Policy makers should keep track of the entire mix of instruments and tailor this to the innovation process of the respective technologies.**

Demand pull instruments like the EEG have a positive impact on innovation because they enable not yet competitive technologies to make a return on investment and by doing so create a niche market in which the new technologies can evolve and later become competitive with other technologies. The profits made can be invested by manufacturers in further innovative activities and in expanding production capacities. This lowers technology costs which in turn leads to greater expansion and triggers a self-reinforcing process that helps to overcome current path dependencies in the energy system.

- **Promoting demand is essential for the transformation of the energy system, but support must be adapted in line with the rising competitiveness of the promoted technologies.**

The **promotion of research and development** is also vital for green change. Technology promotion is particularly effective if it is designed as collaborative research, encompasses systemic aspects of the innovation process and facilitates the access to and exchange of knowledge via networks of different actors. This can be done indirectly through the specific national design of the innovation system and can also be supported directly by policies promoting collaborative research. The systemic instruments used must consider not only national but especially international knowledge exchange so that Germany can keep abreast of a fast moving technology environment.

- **Research promotion should use systemic instruments to improve the flow of knowledge and integrate as many different actors as possible in networks.**

- **Research and innovation policy should focus more on the access to international knowledge, through international cooperative research, for instance, or researcher mobility.**

The consistency of the instrument mix with the political targets set for the expansion of renewable energies and the **credible political commitment** of Germany to these targets have a decisive influence on corporate investments in research and development. In order to be able to compete technologically, a long-term planning horizon is required based on stable long-term objectives and predictable instruments, among other things. As the example of nuclear phase-out shows, firm exit plans send clear political signals about the support of green niche technologies. Compared to this, the lack of a clear exit plan for coal-fired power generation and the weakness of the EU Emissions Trading System represent opportunities not taken to demonstrate a strong political will in favour of the *Energiewende*.

- **A credible political commitment to the *Energiewende* has a crucial influence on private innovation activities and should therefore be enhanced.**

- **Not only political targets and instruments to promote renewable energies are needed for the policy mix to be accorded a high degree of credibility and consistency, but also instruments for the regulated phase-out of rival technologies that are damaging the climate.**

The effect of the German policy mix on **market development abroad** and vice versa should no longer be underestimated in view of global learning curves. The global perspective is very important to fully grasp the macroeconomic effects of expanding renewable power generation technologies, especially for the impending phase of integration into the energy markets. So far, it can be concluded that the expansion of renewable energies in Germany has had different distributional effects, but that the net macroeconomic effects are positive with a view to growth and jobs.

- **Political debates should place greater emphasis on how the *Energiewende* has strengthened the economy and prosperity.**

- **The German policy mix should be aimed at the advantages of continued expansion that result from developing new markets and the associated macroeconomic effects.**

The global expansion of renewable energies is very important for **climate policy** and to achieve the post-2015 development goals, because it reduces the carbon intensity of global production chains and lowers technology costs through economies of scale and learning effects. As a result it enables countries (still) developing their electricity supply to access renewable energies more cost-effectively. The existence of cost-effective renewable power generation technologies also represents a major building block for the Climate Conference in Paris. A necessary condition for the continued reduction of technology costs and CO_2 emissions is the creation and strengthening of the global markets for renewable power generation technologies.

- **Germany has to push for a credible, international climate agreement with ambitious and long-term targets that sends clear signals about the decarbonisation of the global energy system.**

To sum up, it can be stated that the green change in power generation technologies embarked upon globally and in Germany is moving in the right direction, but must continue to be reinforced in view of the ambitious energy and climate goals and its many associated benefits. However, the **innovation climate** for renewable power generation technologies in Germany has **worsened** since 2011. This is demonstrated, for example, by falling trends in the patent applications of German inventors and technological competitiveness, the declining innovation expenditure of the German manufacturers of renewable power generation technologies and the fast-paced technology catch-up taking place in Asian countries, in particular. For Germany to continue to be ranked among the world's green technological leaders, these warning signals should be taken seriously and the necessary adjustments made to the policy mix.

- **The German innovation climate for the *Energiewende* needs to be specifically monitored in order to identify negative trends early on.**

- **To avoid curbing Germany's innovation momentum, measures should be taken promptly that maintain and further extend the benefits of transforming the energy system.**

5.2 Research implications

The empirical studies conducted in GRETCHEN have led to new insights into the interaction of different instruments and the policy mix as a whole. However, several questions concerning the effect of the policy mix on technological and structural change remain unanswered. Based on this, two main recommendations can be derived for future research in the fields of the economics of climate change, the economic evaluation of the *Energiewende*, and environmental innovations:

- An **improved database** is essential for further research, so that the first action must be to close any gaps in the national and international data (especially longer time series, company data).

- The impact analysis of the policy mix should be extended to **other countries and sectors**; this involves combining and further developing quantitative and qualitative research methods.

Data availability plays an essential role for the scientific research and systematic evaluation of political instruments and the policy mix as a whole. In particular, longer time series are needed in order to be able to better map the development and influence of policy measures in quantitative terms. It is therefore recommended to extend the “Renewable Energies in Figures” by variables important for quantifying the policy mix and its effect. These include, for example, the imports and exports of renewable power generation technologies, the levelized cost of electricity generation of the different technologies, the strength of the political will and the consistency of the policy mix. The provision of such data would greatly improve the monitoring of the innovation system in the field of renewable energies and supply all the actors in the innovation system with important information. This is not only valid for Germany but equally for other nations because many of the conclusions about the effect of the German policy mix can only be analysed properly by integrating international policy and market developments.

The GRETCHEN survey of manufacturers of renewable power generation technologies has proven a promising instrument to collect data on the link between the policy mix and innovation. Three strands of future research result in this regard: First, it is recommended to set up a periodic **innovation survey** of the manufacturers and suppliers of all technologies relevant for the *Energiewende*. Second, the GRETCHEN survey should also be conducted in other important manufacturing countries with a different policy mix in order to learn more about the impact on innovation of its consistency, credibility and coherence. Third, questions about the policy mix should be added to current, already established innovation surveys such as the Europe-wide Community Innovation Survey, to better understand the significance of political factors determining green change in other industries as well.

Because it has always been difficult to measure innovation and technological change, **different indicators of technological and structural change** were compiled and evaluated as part of the GRETCHEN project. This showed that the choice of variable can significantly influence the results. It is therefore recommended for future studies and evaluations to rely on a large variety of innovation indicators in order to obtain the full picture. Due to the problems with the data situation and the high degree of complexity, more research approaches should be used that combine quantitative and qualitative analyses in order to gain a better understanding of the links between the policy mix and innovation. In addition, **new approaches or methods** to capture the impact of different policy measures or multiple factors should be developed that specifically target their interaction or that are tailored to specific phases of the innovation process.

A huge challenge is the **development of macroeconomic models** able to illustrate complex relationships at an international level as well as the interaction of national policy design and global developments and which can support national policy makers in their decisions. More micro- and macroeconomic perspectives should be integrated in order to better illustrate the impact interactions. When doing so, developments on the key markets for renewable power generation technologies should be monitored in more detail.

Overall, there are several **applications** for the developed policy mix concept. These include extending the analyses to other emerging technologies (e.g. complementary climate technologies like storage systems, fuel cells and energy efficiency technologies) and to other markets and countries (e.g. Asia, USA). For wind power and photovoltaics, the analysis could be extended to niches or parts of the value chain that hold promising future prospects for German companies due to their complexity or market proximity. The overriding objective is always to derive policy recommendations on how to steer and accelerate green change from an improved understanding of how the policy mix affects the innovation system.

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The following researchers worked on the project:

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