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

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Abstract

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

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

1 Introduction

Climate change resulting from anthropogenic greenhouse gas (GHG) emissions is a major challenge for societies worldwide (IPCC, 2007a). While the power sector is one of the main sources of GHG emissions, it also has high decarbonisation potential[1]: The International Energy Agency (2010) assumes that it could contribute over 40% of the 21 billion tonnes CO_2 emission abatements that are needed by 2035 to achieve the 450ppm target[2]. Besides unlocking the large demand-side efficiency potential, the development and diffusion of renewable energy technologies (RET), carbon capture and storage (CCS) and highly efficient fossil fuel power plants are key levers for achieving these emission cuts[3]. While the IEA estimates that the specific CO_2 emissions of power generation will drop to a quarter of today's value by 2035, other scenarios are even more aggressive (IPCC, 2011; Krey and Clarke, 2011 provide recent Scenario overviews). Notwithstanding the differences in the assumptions of each scenario, they all conclude that technological change (TC) must be accelerated and redirected onto a low-carbon pathway if the 450 parts-per-million (ppm) target is to be achieved. This has to happen in a timely manner, given that global emissions continue to rise strongly (ESRL, 2010). In spite of the fact that low-carbon TC is the most important factor for achieving the 450 ppm target, it is not yet well understood (Pizer and Popp, 2008). This paper focuses on the role of policy, which aims at the decarbonisation of the power sector, in inducing an acceleration and redirection of technological change (TC).

The European Union (EU) and its member states have introduced and reinforced climate policy and climate-relevant technology policies (del Río, 2009; Rogge et al., 2011b; Sijm, 2005) with the aims to reduce emissions at low cost and spur innovation (European Commission, 2005). The few studies to date that have analysed the effects of these new policies (for an overview over the role of the EU ETS see e.g., Zhang and Wei, 2010) on low-carbon TC mostly stem from the neoclassical environmental economic school or from evolutionary innovation studies. While environmental economists look at the role of policy for inducing innovation at a sectoral level, assuming rational firm behaviour (for a recent overview see e.g., Popp et al., 2010), evolutionary scholars stress the role of the tacitness of technology and firm heterogeneity (Dosi, 1997; Nelson and Winter, 1982). They argue that in order to study the role of policy in the acceleration and redirection of TC, it is vital to look at the level at which innovation takes place: the firm level[4].

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

[1] The electricity sector might also play an important role in decarbonising other sectors, e.g., the transport sector via e-mobility (van Essen and Kampman, 2011).

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

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

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

encompasses the production and sale of new technologies by producers and the adoption of these technologies by users (Ashford, 1993; Gort and Konakayama, 1982) and refers to the last stage of Schumpeter's definition (diffusion).

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

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

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

2 Framework

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

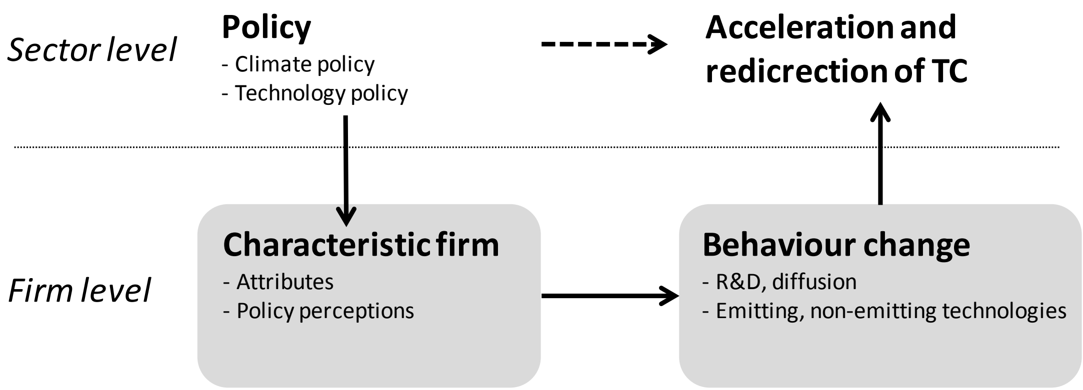

Figure 1 Framework for analysing the role of firm heterogeneity in the effects of policy on technological change. The grey boxes show the two analytical steps we perform in this study.

2.1 Acceleration and redirection of technological change

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

2.2 Policy

The policy mix aiming at low-carbon TC in the power sector can be differentiated into climate policy and technology policies (e.g., Azar and Sandén, 2011; Jaffe et al., 2005). Climate policy alters the competitiveness of technologies by putting a price on carbon, such as through a carbon tax or an emission cap and trade system. Emitting technologies are financially disadvantaged, whereas non-emitting technologies are not directly affected but may benefit from increased electricity prices. Nevertheless, climate policy is regarded as technology neutral as emissions are targeted independently from the source (Azar and Sandén, 2011). In the European Union it is operationalized via the EU ETS (European Commission, 2005, 2010a) and via emission reduction targets, which have been shown to be an important element of the climate policy mix (Rogge and Hoffmann, 2010). Besides these technology-neutral policies, technology policies, which – as the name implies – target specific technologies in different ways, are an important element in the policy mix. Among technology policies, technology-push and technology-specific demand-pull instruments can be distinguished (Rennings, 2000; Taylor, 2008). The former are designed to induce or directly fund private R&D in order to improve technologies in important performance dimensions (Nemet, 2009) - examples are the R&D subsidies devoted to CCS and RET by the EU (European Commission, 2009b). The latter create demand for technologies whose competitiveness is currently inferior to other technologies but which have significant cost reduction potential (Taylor, 2008). In the power sector, preferential feed-in tariffs or quotas for renewable energy technologies are instruments which are often utilised (Mendonça, 2010; Ringel, 2006). While some of the technology specific policies are enforced by the EU, most renewable energy policies are introduced on a local level. Those national policies show different levels of stringency depending on the instrument and design features. Table A1 in the Annex shows the national renewable energy polices enacted during the period of 2005 to 2009 according to the IEA "Global Renewable Energy Policies and Measures Database" (IEA, 2012).

2.3 Characteristic heterogeneity: attributes and policy perceptions

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

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

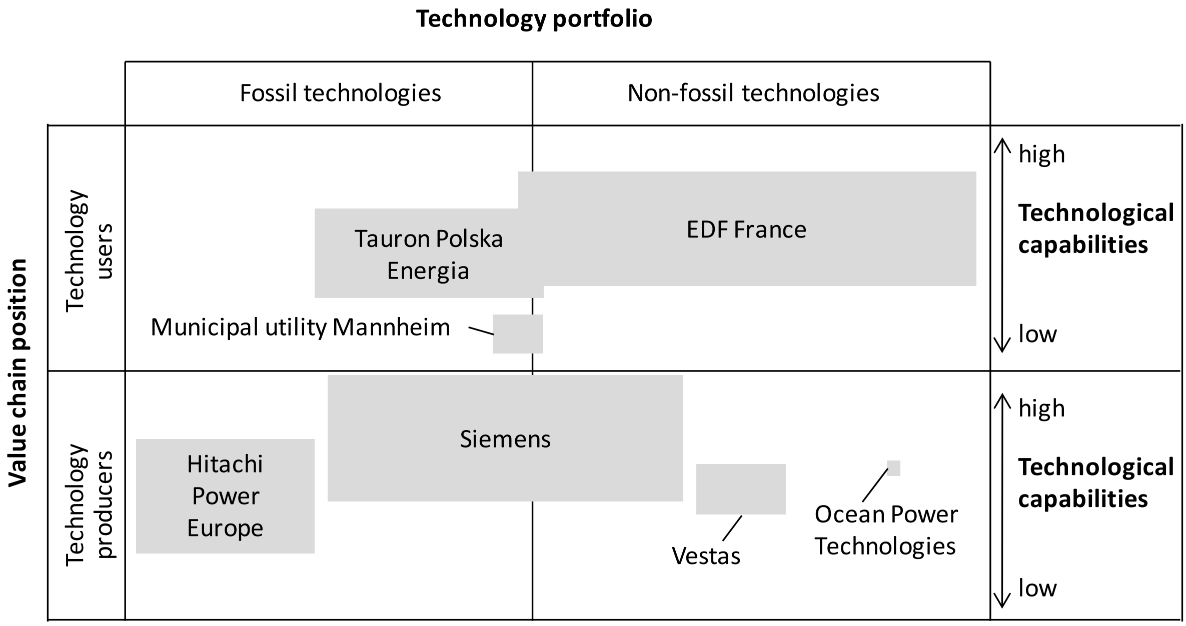

Figure 2 The four heterogeneity attributes and example firms. The size of the firm is represented by the size of the grey squares. The figure is not to scale but sketches the very large heterogeneity of some example firms. These examples were picked irrespective of their (anonymous) participation in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

Second, regarding the value chain position of the firms (Rogge et al., 2011b), we differentiate between technology users and technology producers. In the power sector, the term technology user refers to power generators who select between alternative electricity generation technologies when building new capacity. Above that, users are the firms directly regulated by the EU ETS. The term technology producer refers to power generation equipment suppliers.

Third, firms' *technology portfolios* can differ significantly as firms can either be active in one or several technologies, each of which can be GHG emitting or non-emitting. In the power sector, GHG emitting technologies are based on the combustion of fossil fuels, whereas non-emitting technologies use other sources of energy. We therefore differentiate between *fossil* and *non-fossil* technologies. The composition of the portfolio thus determines the emission intensity of the portfolio (Rogge et al., 2011b) and the impact of a policy on a firm (see below).

Finally, a firm can have high or low *technological capabilities*, i.e. "patents protected by law, technological knowledge, and production skills that are valuable and difficult to imitate by competitors" (Lee et al., 2001, p. 618). It has been shown that firms with higher technological capabilities tend to react with more innovation to external stimuli, such as the introduction of policy (Rosenberg, 1974).

Organisational theory scholars argue that besides their attributes corporate perceptions are essential determinants of firms' behaviour changes (Bansal, 2003; Buysse and Verbeke, 2003; Dutton and Jackson, 1987). Each individual firm perceives its business environment and changes therein (e.g., via the introduction of climate policy) differently (Dosi et al., 1997). Firms can perceive such changes neutrally or as opportunities or threats to different degrees (Barr et al., 1992; Dutton and Jackson, 1987). Besides their heterogeneous attributes, firms' "limited understanding [...] of the environment in which they are embedded" leads to different perceptions (Dosi et al., 1997, P. 1540). Furthermore, firms are active in different countries, i.e., embedded in dissimilar environments with different policies (compare Table A1 in the Annex) which are of various stringency levels and can be dynamic over time[5]. This of course also impacts on the firms' policy perceptions. We summarize the attributes and policy perceptions under the term *characteristic heterogeneity*.

2.4 Behavioural heterogeneity: changes in R&D and diffusion activities

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

[5] For more details on the national renewable energy policies in the EU member states see e.g., Blok (2006), Klessmann et al. (2011) and Fouquet & Johannson (2008).

behavioural change is the first step towards answering our research question. In order to better understand which firms follow which specific pattern, we also analyse their characteristics.

3 Methodology

3.1 Survey and sample

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

Table 1 Country of origin of respondents[6]

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

The analyses performed in this study are based on the answers of 201 firms, 65 power generators and 136 technology providers. This represents a response rate of 13.1% and 12.5% of the population of 496 power generators and 1088 technology providers respectively. The population of power generators in each country was identified based on the EU's “Community Independent Transaction Log” (CITL) comprising all firms which fall under the EU ETS. The technology provider population in each country was identified on the basis of the “KKS” power plant classification system of “VGB Powertech”, the respective European industrial activity classifications (NACE Rev.2) and the firm registry “Amadeus”. Table 1 shows the respondents’ countries of origin. As a result and in contrast to most other survey-based studies on the power sector, our dataset also includes firms which are not publically listed. Regarding power generators, the strong bias towards Germany is partially based on its very high number of (small) firms compared to the other countries. A similar trend can be observed in the producer sample. With the exception of France and the UK - which are underrepresented - these numbers provide representative drawings of the entire population of technology providers. Of the power generators, 76% have undertaken adoption measures (i.e., invested in new plants) and 37% have conducted R&D within the last ten years, which is our time horizon for innovation observations. As expected, the number of producers undertaking

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

R&D activities is higher, namely 69%. The remaining 31% focus on technology assembly and do not invest in formal R&D.

3.2 Variables

3.2.1 Behaviour change

In order to capture behaviour changes, we distinguish between R&D and diffusion for both fossil (lignite, hard coal, gas, oil) and non-fossil (nuclear, renewable) technologies[7], resulting in four variables. We surveyed the four variables by asking how the monetary volumes of R&D investments and investments in new plants (power generators) or sales (technology providers) have changed in the last five years (2005-2009), since climate policy was introduced, compared to the previous five years (2000-2004, this period thus serves as benchmark.) The answer categories of the five-point Likert scale ranged from "dropped sharply" (-2) via "no change" (0) to "rose sharply" (+2). This is of course a relatively rough gauge, however firms are typically unwilling to report exact investments. The statistical purpose of all variables, how they were queried in the survey or indirectly constructed as well as their descriptive statistics are depicted in Table 2.

3.2.2 Climate and technology policy

Five policy variables are taken into account, each representing policies that aim to induce a low-carbon transition in the power sector. The European Union's *Emission Trading System (ETS)* is considered via two variables as we distinguish the more short-term and lax *phases 1 and 2* (from 2005 to 2012) from the medium-term and more stringent *phase 3* (from 2013 to 2020). In the first two phases, the allowances market was rather long, i.e., over-allocations of emission rights to many firms were common (Betz et al., 2006; Ellerman and Buchner, 2007). This situation changes in phase three when a rising share of emission rights will have to be auctioned. Though the market might still be long as the financial and resulting economic crisis led to decreased industrial production and thus electricity consumption (Point Carbon, 2011), an individual firm will have to spend money on each emission allowance via the auctioning. Furthermore we consider *long-term targets (LTT)*, which represent European and global GHG emission reduction targets for 2020. Besides climate policy, two types of technology policy instruments were considered: *technology push* (such as R&D subsidies) and *technology-specific demand-pull* measures (such as preferential feed-in tariffs for RET).

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

Table 2 Operationalization and descriptive statistics of all variables

		variable	question asked / variable constructed	min	max	mean	std.dev.
variables used in cluster analysis	innovation pattern change	non-fossil R&D	"How has your non-fossil investment volume for new installations changed in the last five years (2005-2009) compared to the previous five year period (2000-2004)?"	-2.00	2.00	.53	.79
		fossil R&D	"How has your total RD&D investment volume changed in the last five years (2005-2009) compared to the previous five year period (2000-2004)?"	-2.00	2.00	.10	.54
		non-fossil diffusion	"How has your turnover with non-fossil products (TP) / non-fossil investment volume for new installations (PG) changed in the last five years (2005-2009) compared to the previous five year period (2000-2004)?"	-2.00	2.00	.83	.91
		fossil diffusion	"How has your turnover with fossil products (TP) / fossil investment volume for new installations (PG) changed in the last five years (2005-2009) compared to the previous five year period (2000-2004)?"	-2.00	2.00	.22	.77
variables used in parametric tests	resources & capabilities	vc position*	dummy variable (1: PG, 2: TP)	1.00	2.00	1.68	.47
		Size (turnover)	"What was the total company turnover in 2008?" *(1: < 2 million €, ... 6: > 5 billion €)*	.00	6.00	2.80	1.51
		share fossil (in %)	"What is the percentage of fossil fuel based porducts in your total turnover (TP) / generation in your total electricity generation (PG)?"	.00	100.00	35.44	42.45
		Tech capabilities	standardized and factorised share of R&D expenditure to sales and of R&D staff to total employees	-.45	6.06	.00	.91
	policy perception	ETS 1 & 2	"To what extent is your company negatively or positively affected by the EU emissions trading in the period 2005-2012?"	-2.00	2.00	.19	.81
		ETS 3	"To what extent is your company negatively or positively affected by the EU emissions trading in the period 2013-2020?"	-2.00	2.00	.11	.99
		LTT	"To what extent is your company negatively or positively affected by long-term European and global reduction targets for greenhouse gases as in 2020?"	-2.00	2.00	.35	1.17
		Tech.-push policy	"To what extent is your company negatively or positively affected by EU & national policies promoting R&D and innovation over the last five years (2005-2009)?"	-2.00	2.00	.38	.83
		RET-pull policy	"To what extent is your company negatively or positively affected by the policy framework regarding renewable energies over the last five years (2005-2009)?"	-2.00	2.00	.98	1.01

TP: Technology Providers; PG: Power Generators

3.2.3 Firms' attributes

As mentioned above, we use four variables to describe the firms' structure and capabilities. The *value chain position* is represented via a dummy variable, which ascribes the value 1 to power generators and 2 to technology providers. The *size* of the firm is expressed by its turnover. We surveyed the turnover via exponentially rising answer categories. The *share of fossil technologies* in a firm's generation portfolio (power generators) or its sales (technology providers) as of 2009 describes its technology portfolio and can range from 0 to 100%. The *technological capabilities* were measured via two factorised[8] items, the percentage of R&D expenses per turnover and the percentage of R&D employees per overall staff. As for all supplier dominated sectors, in the power sector

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

the rate of R&D activity differs strongly between users and producers of technology and thus correlates with the value chain step dummy. Hence, we standardized the variable per value chain step via z-scores before merging the sub-samples. National subsidiaries of international firms active in more than one of the countries included in our survey were treated as individual firms.

3.3 Statistical Methodology

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

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

4 Results

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

4.1 Statistical results

4.1.1 Behavioural heterogeneity

Our analysis resulted in seven clusters[9]. Table 3 shows the respective clusters, their centres (means) with respect to the changes in R&D and diffusion activity of fossil and non-fossil technologies as well as their size in absolute and relative terms. The names of the clusters are chosen to summarize their behaviour change. Generally three groups can be identified (compare the three shades of grey in Table 1).

First, almost 40% of the firms (*Business as usual, BAU*) show no major changes regarding their behaviour. Second, 15 firms (*fossil diffusion*) contribute to increased fossil technology diffusion (1.67 out of a maximum possible

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

increase of 2) and thus play a rather controversial role in the low-carbon TC. Third, more than 50% of the firms contribute to low-carbon TC but to varying degrees and in different ways. This indicates that on the one hand some acceleration and redirection of TC is taking place in the sector, but that on the other hand the contribution of many firms is limited and of some might even be controversial.

Table 3 Changes in behaviour – cluster centres and size

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

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

4.1.2 Characteristic heterogeneity

The results of the cluster comparison regarding the four attributes and five policy perceptions of the firms are summarised in Table 2. This shows the mean and standard deviation (std d) of the respective variables as well as the cluster size. For all variables, the Kruskal-Wallis tests resulted in a rejection of the null-hypothesis. Hence, at least one cluster differs significantly (at p<5%) on each variable from at least one other cluster. In order to better understand the differences between the clusters, we used the *BAU* cluster – the biggest cluster which does not show major changes in behaviour – as a reference case and compared each cluster against it to find significant differences (at p<5%) via Mann-Whitney tests, adjusting the significance level with Bonferroni corrections, as mentioned above. In Table 4 the means of the variables significantly different to BAU are underlined[10].

Several clusters differ strongly regarding both the firms' attributes and their policy perceptions. While the BAU cluster seems to contain very heterogeneous firms (the variance of the distribution is quite high), other clusters show strong peculiarities, e.g., the fact that all firms in the *fossil exit* cluster are power generators. In the next section, we will show that firms' heterogeneity of attributes and policy perceptions can be linked - to some extent - to their dissimilar behaviour changes. Therefore, in order to better understand the role of firm heterogeneity for the role of policy for TC, we now turn to each individual cluster and discuss both the behavioural and characteristic aspects of heterogeneity.

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

Table 4 Comparison of the clusters' characteristics, i.e., attributes and policy perceptions

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

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

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

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

4.2.1 Business as usual (BAU) Cluster

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

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

4.2.2 Fossil diffusion Cluster

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

Firms in the *fossil diffusion* cluster show several peculiarities. About 70% are power generators, which is a significantly higher rate than in the *BAU* cluster. They are relatively large in size and their portfolios already tend to be dominated by fossil technologies – significantly more than those of the firms in the *BAU* cluster. Their technological capabilities are rather low on average, and their perception of climate policy is slightly positive regarding ETS 1&2 and negative (significantly more than that of *BAU* firms) regarding ETS 3 and LTT. Technology policies are perceived relatively neutrally on average (but variant).

4.2.3 Clean focus Cluster

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

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

4.2.4 Overall diffusion Cluster

These 17 firms contributed to a mere acceleration of TC. They strongly increased their technology diffusion activities in both technological areas while keeping their R&D activities constant. Thus, their contribution to low-carbon TC in the sector was limited[11].

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

4.2.5 Overall innovation Cluster

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

About one third of the firms are power generators, two thirds technology providers. They are the largest firms on

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

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

4.2.6 Clean Shift Cluster

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

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

4.2.7 Fossil Exit Cluster

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

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

4.3 Summary of results

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

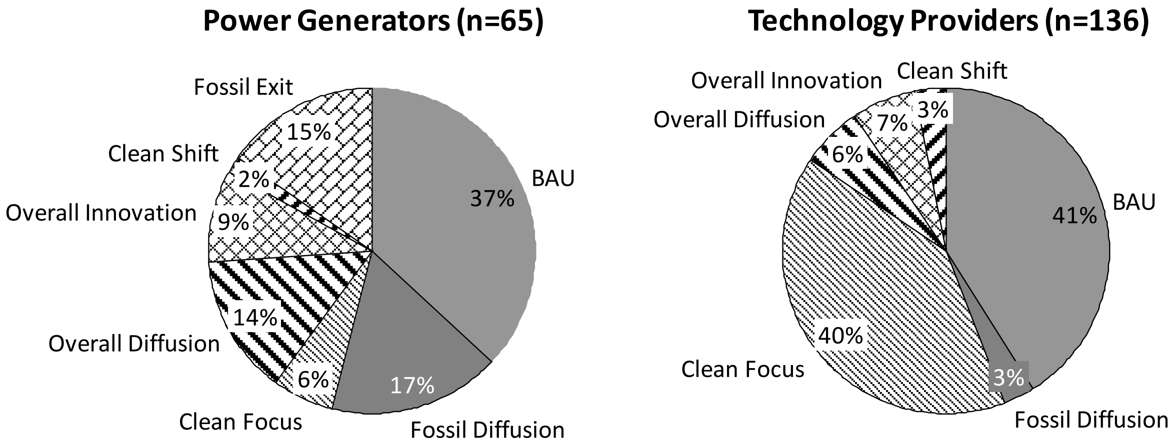

Figure 3 Distribution of the power generators (left) and technology providers (right) across the clusters

While the percentage of *BAU* is similar for both value chain steps, we find remarkable differences for the other firms. Power generators show very different behaviour changes, e.g., 17% increasing their fossil adoption activities and 15% reducing them. This picture is different for technology providers, where most of the non-*BAU* firms follow the *clean focus* pattern. From an evolutionary standpoint this is important as in the supplier dominated electricity sector it indicates that the firms relevant for creating novelty through R&D (technology providers) are contributing more to low-carbon TC than the regulated ones (power generators). Policy should therefore secure the growth and survival of these firms in order to assure TC at the sector-level. Table 5 summarizes all findings regarding the behavioural and characteristic heterogeneity from which we draw implications for policy makers (see next section).

Table 5 Summary of the findings

Cluster	Behavioural heterogeneity	Characteristic heterogeneity	
	Cluster's contribution to low-Carbon TC	Attributes	Policy perceptions
BAU	• No contribution to acceleration or redirection • Large inertia due to large size of cluster	• Medium values on all resources and capability variables	• Rather neutral perception of climate policy (LTT slightly positive) • Slightly positive perception of technology push policy • Rather positive perception of RET-pull policy
Fossil Diffusion	• Controversial via redirection towards fossil fuels	• Power generators • Large firms • Relatively fossil portfolios • Low technological capabilities	• Rather negative perception of climate policy (except for ETS 1&2) • Rather neutral perception of technology policy
Clean Focus	• Strong via acceleration and redirection • Strong via large size of cluster	• Technology providers • Medium size • Non-fossil portfolios • Moderate technological capabilities	• Throughout positive perception of climate policy • Throughout positive perception of technology policy (especially RET-pull)
Overall Diffusion	• Limited via acceleration	• Large firms • Diversified portfolios • Relatively low technological capabilities	• Rather neutral perception of climate policy • Neutral perception of technology push policy • Positive perception of RET-pull policy
Overall Innovation	• Medium via acceleration on both dimensions R&D and diffusion	• Large firms • Diversified portfolios • High technological capabilities	• Throughout slightly positive perception of climate policy • Throughout positive perception of technology policy
Clean Shift	• Strong via redirection • But limited due to small size of cluster	• Technology providers • Medium size • Non-fossil portfolios • High technological capabilities	• Throughout positive perception of climate policy • Slightly negative perception of technology push policy • Very positive perception of RET pull policy
Fossil Exit	• Medium via weakening of fossil technologies • But overall deceleration • Limited by relatively small size of cluster	• Power generators • Small size • Fossil portfolios • Low technological capabilities	• Negative perception of climate policy (especially LTT) • Slightly negative perception of technology push policy • Slightly positive perception of RET-pull policy

5 Policy implications

Our study provides first feedback on the decarbonisation of the power sector via TC – an important objective of European energy and climate policy (European Commission, 2005, 2010a). Firstly, our results show that firms' contribution to low-carbon TC differ strongly. The fact that about 40% of the firms do not contribute to an acceleration and redirection of TC and another almost 8% contribute to a redirection to the fossil direction is important information for policy makers which casts doubt upon whether the current policy mix is able to trigger an acceleration and redirection of TC in the magnitude needed to meet the 450ppm target. Our results thus imply that the policy mix might need to become more effective.

Secondly, the comparison of firms' attributes and policy perceptions provides novel information on the characteristic heterogeneity of differently behaving firms. While the policy mix might accomplish its purpose for some firms, other firms with potentially very specific characteristics need further incentives if large scale changes are to be achieved. Therefore, we hereafter proceed in two steps: first, we shortly discuss the firms' contributions to the acceleration and redirection of TC and derive implications for policy; second, we propose several policy measures and discuss how they could alter the behaviour of the firm groups and thereby accelerate and redirect TC, taking into account more recent market and policy developments.

5.1 Firms' differing contributions, implications for policy

The largest group of firms (*BAU*) does not significantly change its behaviour. Hence, they unveil the large inertia present in the sector. The main policy task is to stimulate increased activities in a low-carbon direction. Interestingly, the firms in this cluster are not a very specific group but are instead highly heterogeneous regarding their attributes. One commonality appears to be the rather neutral perception of policies. In other words, climate and technology policy does not yet constitute a decisive element of their business environment (compare Rogge et al., 2011a) pointing to a certain lack of stringency of the current policy mix. In order to become a decisive element, the stringency of policy needs to be increased. Additionally, providing a higher level of regulatory certainty might break-up the inert behaviour of these firms (Engau and Hoffmann, 2011a; Engau and Hoffmann, 2011b; Hoffmann et al., 2009).

The fact that climate policy did not prevent power generators (*fossil diffusion*) with fossil fuel-heavy portfolios from predominantly investing in new fossil technology might seemingly point to a strong firm technology lock-in. However, the portfolios of these firms are not as fossil technology-heavy as those in the *fossil exit* cluster. An explanation might be the inverted incentives set by the allocation rules under the first phases of EU emission trading – this would explain why these firms perceive ETS 1&2 rather positively whereas they exhibit a negative perception of ETS 3 and LTT. While Ellerman and colleagues (2010) expect such effects ex-ante based on their economic models, first empirical studies (Schmidt et al., 2011) affirm these expectations. These effects are limited to the first two phases of the EU ETS in the power sector, as future allowances will mainly be allocated via auctioning. However, even auctioning might not result in major behaviour changes, given the current situation: the economic crisis in Europe raises the expectation that the allowance market will be long for several years, resulting in low carbon prices (Point Carbon, 2011), which in turn results in a low incentive to alter the behaviour of the firms in this cluster. Measures that prevent a price decline need to be taken, against which, however, lobbying pressure of the firms can be expected.

Firms accelerating TC without clearly redirecting it (*overall innovation* and *overall diffusion*) are mainly larger firms with mixed portfolios. Their contribution to low-carbon TC depends strongly on the kind of investments made in fossil technologies. Should these investments lead to the significant decarbonisation of these technologies (e.g. via R&D in CCS) their contribution can be very important. Therefore, policy needs to ensure that fossil innovation is targeting substantial emission reductions and not incremental ones, which instead of opening it for new non-fossil technologies rather cement the fossil regime and thereby exacerbate or delay deep emission cuts on a system level.

For another group of firms, the fossil exit cluster, climate and technology policy has served the purpose of decarbonisation only to a certain point. These power generators are heavily invested in fossil plants and directly targeted by climate policy. They perceive the new policy as a threat and took a first step by strongly reducing fossil investments. However, the policy mix does not (yet) prompt the second step of decarbonisation: investments in non-fossil technologies. Besides the potential influence of investment cycles, these results point to a certain lock-in of these firms in a fossil trajectory and/or the role of regulatory uncertainty in their hesitant behaviour (see also BAU above). Policy thus needs to provide further incentives to become active in technological fields new to a firm backed by higher levels of regulatory certainty.

Finally, two clusters (clean shift, clean focus) have been identified which contribute to a redirection and acceleration of TC. Firms in these clusters perceive climate and technology policy as an opportunity. They are mainly providers of already aligned (non-fossil) technologies which gave up their small existing shares in fossil technology. Interestingly, the policy mix aiming at the decarbonisation of the sector seems to have only fully achieved its target for technology providers, though these companies are only indirectly affected by climate policy. As the power sector is a supplier dominated sector (Pavitt, 1984), the firms in these clusters are highly relevant for low-carbon technological change and should be further supported.

5.2 Policy measures and their potential effects on the heterogeneous firms

Having discussed the differing roles of firms and the resulting policy implications, we now propose a non-exhaustive list of policy measures on different institutional levels which could support the derived policy implications. We differentiate three institutional levels, mainly focusing on the EU level. Table 6 summarises the proposed measures, their general desired effects and how they could trigger behaviour changes of the various firm groups.

Table 6 Policy recommendations and their potential effects

<table>
<tr><th></th><th>Policy measure</th><th>General effects</th><th>Potential effects on clusters</th></tr>
<tr><td rowspan="4">EU</td><td>Formulate targets past 2020</td><td>• Reduce of regulatory uncertainty</td><td>• Improve planning and strategy making for all firms</td></tr>
<tr><td>Increase 2020 target beyond 20% and lower cap</td><td>• Increase stringency of ETS</td><td rowspan="3">• Break inertia of BAU by raising their climate policy perception
• Make incremental reductions less attractive and thereby alter investments of Fossil Diffusion
• Redirect innovation of Overall Innovation and Overall Diffusion towards low-carbon by raising their climate policy perception</td></tr>
<tr><td>Decrease freely allocated allowances for industry sectors</td><td>• Increase stringency of ETS
• Counteract of price decline due to economic crisis</td></tr>
<tr><td>Introduce price floors for ETS</td><td>• Counteract price decline due to economic crisis</td></tr>
</table>

<table>
<tr><td rowspan="3"></td><td></td><td>• Reduce regulatory uncertainty</td><td>• Encourage Clean Shift and Clean Focus to continue their strategy</td></tr>
<tr><td>apply "innovation / technology accelerator" to power sector</td><td>• Set positive incentive to become innovative and invest in demonstration</td><td>• Break inertia of BAU by raising their climate policy perception
• Trigger second step of behaviour change of Fossil Exit</td></tr>
<tr><td>Re-focus R&D support policies</td><td>• Avoid incentives that support fossil incremental</td><td rowspan="2">• Encourage firms to strongly increase investments into low-carbon R&D (BAU, Overall Innovation)</td></tr>
<tr><td rowspan="2">National</td><td>Harmonize R&D policy support with EU targets and instruments</td><td>• Avoid national policy incentives undermining EU policies</td></tr>
<tr><td>Expand technology-specific support schemes for RET to more member states</td><td>• Provide further incentives for clean technology diffusion</td><td rowspan="2">• Ensure survival and provide new opportunities to grow for low-carbon technology providers (clean shift, clean focus)
• Incentive for innovative firms to redirect their activities towards low-carbon technologies as they innovate for global markets (partly BAU, Overall Innovation)</td></tr>
<tr><td>International</td><td>Support emerging economies / developing countries in their mitigation activities (e.g., via NAMA funding)</td><td>• Spur the creation of large markets for abatement technologies outside the EU</td></tr>
<tr><td>All</td><td>Withstand lobbying pressure of threatened firms</td><td>• Increase stringency of ETS and technology specific policies
• Avoid policy incentives undermining climate targets</td><td>• Partly shrinking or disappearance of firms in Fossil Diffusion and perhaps BAU cluster</td></tr>
</table>

On the EU level, the first measure we propose is the formulation of targets which reach beyond 2020. The long investment cycles and lead times in the sector demand clearly communicated targets for the time post-2020. In early 2011, the EU formulated a 2050 roadmap (European Commission, 2011a) containing sector-specific targets for 2050 and 2030. However, at least the 2030 targets should be stipulated (currently they range from 54 to 68% reductions compared to 1990 for the power sector) and substantiated with an outlook on future instruments in order to make them credible. This would result in a lower level of regulatory uncertainty and provide an improved basis for investment planning and strategy making for firms in *all clusters*.

In order to increase the stringency of the ETS, we propose two measures. First, to increase the 2020 target beyond 20% reduction and lower the cap accordingly; second, to decrease the allocated allowanced for industry sectors. While the first proposal – 30% for 2020 are being discussed (European Commission, 2010b) – would directly target the power sector and counteract the fact that the market will be long on certificates till 2020 (see above), the second measure would affect the power sector only indirectly. While for the power sector, most emissions will be auctioned, a large amount of emission allowances will still be allocated for free for industry sectors based on performance benchmarks, starting with 80% in 2013 (Clò, 2010; Cooper, 2010; European Commission, 2011b; Parker, 2010). Decreasing the rate of allocated allowances for the industry would increase the demand for credits and thereby counteract the price decline due to the economic crisis thus raising the stringency. To this end, the benchmark rules might be tightened, e.g., for process emissions beyond the allocation of 97% of the historical emissions (European Commission, 2011b).

A further measure against the price decline would be to introduce price floors[12] i.e., setting a minimum price for emission rights. Another effect of such price floors is the reduction of regulatory uncertainty (Hepburn et al., 2006; Neuhoff, 2011). While an ETS without price floors is the better option if its sole objective is to meet an emissions target (Wood and Jotzo, 2011), price floors can support the second target of the EU ETS: "driving global innovation" (European Commission, 2009a, p. 5). The recently enacted Australian emission trading scheme contains a price floor (and ceiling) after the first three years in which the price is fixed (Commonwealth of Australia, 2011).

All three measures – raising the target, decreasing allowances for industry sectors and price floors – are expected to have the following effects on the different clusters. The increased stringency could raise the climate policy perception of the firms in the *BAU, Overall Innovation* and *Overall Diffusion* clusters, thereby breaking the inertia of the first and redirecting the investments of the latter two cluster towards low-carbon. At the same time, it would make incremental reductions less attractive and thus potentially alter the behaviour of the fossil *diffusion cluster*. Finally, firms proactively supporting the redirection and acceleration of TC (*clean shift, clean focus*) would be encouraged to continue their strategy. While each of these measures could produce similar effects on its own, the measures can be combined, e.g., depending on the underlying political and legal practicability.

Another measure we propose is to apply an "innovation/technology accelerator" to the power sector. Such mechanism is discussed for the industry sectors to "reward companies that invest in top performing technology and make significant emission reductions [...] by giving those installations additional free allowances on top of what could be expected from a normal implementation of the benchmark rules" (European Comission, 2010, p. 75). Applying this mechanism to the power sector, could alter the perception of climate policy by linking low-carbon innovation with positive incentives to become innovative and invest in demonstration projects. This might break the inertia of the *BAU*-firms and trigger the second step of behavioural change of *Fossil Exit*-firms.

Regarding fossil R&D support, a re-focus of policies might be considered in order to avoid incentives that lead to incremental change in the fossil regime, preventing non-fossil fuel technologies from becoming competitive and thereby undermining ETS and RET pull policies. Also national R&D policy should be harmonised with such revised EU policies in order to avoid undermining of the latter. Both measures would encourage firms which currently also invest in incremental fossil R&D to re-allocate resources towards R&D in fossil technologies which allow for substantial emission cuts or towards non-fossil technologies (partly *BAU, Overall Innovation*).

This brings us to a measure on the national, i.e., member state level: expanding technology-specific support schemes for RET to more member states and thereby increase the overall demand for RET in the EU. So far, RET demand pull policies in Europe differ substantially (e.g., Klessmann et al., 2011) with high potentials remaining untapped. Similarly, on the international level, large markets for RET could be created by supporting emerging economies and developing countries in their mitigation efforts. Nationally Appropriate Mitigation Actions (NAMAs), i.e., efforts to scale up GHG emission abatement in developing countries (Hoehne, 2011; UNFCCC, 2011) could be one way. These measures would on the one hand ensure the survival and growth of low-carbon providers (*clean shift, clean focus*) and incentivise large innovative firms, which often innovate for global markets, to redirect their innovation activities towards low-carbon activities (partly *BAU, Overall Innovation*).

Apart from concrete measures, technological change at the sector level can mean that certain firms dwindle in size

[12] Most recent studies comparing emissions trading schemes with and without price floors prefer schemes with floors (see e.g., Hepburn et al., 2006; Philibert, 2009; Wood and Jotzo, 2011).

or even disappear as market shares are taken over from firms which are more adapted to the new situation (Smith et al., 2005). The resistance of these firms can result in lobbying pressure on any institutional level to decrease stringency (Hepburn et al., 2006). Policy makers at all institutional levels should be prepared for these pressures and need to withstand them.

Finally, in order to result at a stringent and consistent (Kern and Howlett, 2009) mix of climate and technology policies, all measures need to orient themselves along the same decarbonisation goals. However, designing a consistent and effective policy mix which is congruent to long-term targets is complicated in the political reality (Kern and Howlett, 2009; Meadowcroft, 2011). The EU generally has longer political time constants than those of the national governments in the member states and “avoids [...] to a large extent the politics of the party [...]. This results in the fact that apolitical EU civil servants rather than partisan legislators and their staffs are the primary drafters of legislation, and base their decisions primarily on technical and economic [and not political] grounds” (Schmidt, 2006, p. 105). For instance, pressures and lobbying from the aforementioned threatened firms can be more easily resisted by the EU than national governments. Hence, the EU should keep its guiding function for climate policy and enhance its role for coordinating technology and climate policies.

6 Conclusions

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

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

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A Annex

Table A1 Renewable energy policies enacted in the analysed countries in the period 2005 to 2009 according to the *IEA Global Renewable Energy Policies and Measures Database* (IEA, 2012)

Country	Name of Policy	Type	Target technology	Year introduced
France	Renewable Energy Feed-In Tariff: Biomass	•Incentives/Subsidies	•Bio-energy	2009 (modified 2011)
	Renewable Energy Feed-In Tariff: Hydropower (IV)	•Incentives/Subsidies •Regulatory Instruments	•Hydropower	2007
	Renewable Energy Feed-in Tariffs (III)	•Incentives/Subsidies •Regulatory Instruments	•Bio-energy •Geothermal •Solar Photovoltaic •Wind	2006
Germany	2009 Amendment of the Renewable Energy Sources Act -EEG-	•Incentives/Subsidies •Policy Processes	•Bio-energy •Geothermal •Hydropower •Solar Photovoltaic •Wind	2009 (revised 2010)
Italy	Renewable energy provisions for the Green Certificates System	•Policy Processes •Tradable Permits	•Bio-energy •Geothermal •Hydropower •Multiple RET •Ocean •Solar •Wind	2008 (revised 2011)
Slovak-Republic	Excise tax exemption for electricity generated from renewable energy sources	•Financial	•Bio-energy •Geothermal •Hydropower •Solar •Wind	2008
	Ordinance: rights and obligations of the electricity market participants	•Regulatory Instruments	•Multiple Renewable Energy Sources	2007
	Act on Energy and amendments	•Regulatory Instruments	•Fossil Fuels •Multiple RET	2005
Spain	Feed-in tariffs for electricity from renewable energy sources (Special regime)	•Incentives/Subsidies	•Bio-energy •Geothermal •Hydropower •Ocean •Solar •Wind	2007 (modified 2009)