UNIVERSITAT DE BARCELONA

Analysis and Evaluation of Climate Change Policies and their Interaction with Technological Change

Stephan Emanuel Joseph

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PhD in Economics

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Für meine Eltern,
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Chapter 1: Introduction

The impacts of climate change are complex and omnipresent, not only affecting ecosystems but clearly as well socioeconomic systems. In its 2014 report the Intergovernmental Panel on Climate Change (Edenhofer et al. 2014) highlighted the possible and severe impacts climate change can cause for a broad set of regions and stakeholders. These include changing in precipitation and the melting of ice caps, negative impacts on crop yields, heatwaves/droughts, floods, wildfires, ocean acidification in order just name a few. Respectively, these impacts affect food supply, submergence of coastal areas and coastal flooding/erosions and terrestrial and marine biodiversity among others.

Today, these impacts are not only well-recognized by researches in the field but as well by a great number of governments around the world. This fact led to the formation of the first global climate agreement signed in December 2015 in Paris and formally known as the "Paris Agreement". Thereby, the 197 participating parties agreed upon, that global warming must be kept below 2 degrees Celsius compared to pre-industrial levels and efforts should be undertaken to keep it even below 1.5 degrees Celsius.

In order to strike out on this path and to assure that the goals are met, participating countries are required to state their intended actions in the so-called "nationally determined contributions" (NDC) which lay out the future national trajectories of how countries plan to cope with their pledges (United Nations 2016a). Since the "5th of October 2016, the conditions to entry into force of the [Paris] Agreement were met" (United Nations 2016b). This means, that more than 55 parties out of the 197 deposited their NDCs accounting for at least 55% of global greenhouse gas emissions. Therefore, the agreement enters into force November the 4th 2016. At the time of writing, additional 28 countries already ratified their actions, hence, summing to a total of 83 parties which formally agree to keep global warming below 2 degrees Celsius. Among these countries are several of the biggest CO_2 emitting countries and economic areas such as Europe, the US, China, and India.

Nevertheless, the Paris Agreement is not the first internationally agreement combating climate change of its kind. Prior to it, the well-known "Kyoto-Protocol" (KP) was adopted on the 11th of December 1997. In its first commitment period from 2008 until 2012, 37 countries plus the European Union committed themselves to reduce their greenhouse gas emissions by at least five percent on average compared to the levels of 1990, and its second commitment period, by at least 18 percent (United Nations 1998). The means of compliance of how the countries achieve the respective reduction are in the hands of each participating party.

However, the KP promote three market-based approaches to facilitate target achievement. These are the "Clean Development Mechanism" (CDM), "Joint Implementation" (JI), and "International Emission Trading". The CDM offers Annex-B countries part of the KP (United Nations 1998) to conduct emission-reduction projects in developing countries. These projects, if eligible, produce certified emission reduction (CER) credits representing the right of emitting one tonne of CO_2 emissions and can be used to comply with the KP commitments. JI, on the other side, are referring to projects conducted among Annex B countries with the final goal to reduce or remove emissions. These joint projects generate emission reduction units which then can be used again to meet the KP targets. Lastly, international emission trading relates to the creation of a common market place where emission certificates can be traded among participants. Hence, parties having an excess of supply are able to sell spare certificates to short parties.

In line with the above outlined Kyoto mechanisms and in order to comply with its pledges, the EU established the first and to this date biggest market place for GHG emissions launched in 2005, the European Union Emission Trading System (EU ETS). Under the trading system heavy-emitting industrial sectors and the energy sector[1] are forced to cover their emissions by European Emission Allowances (EUA) or are subject to heavy fines if they fail to do so. Thereby, the EU ETS relies on the mechanisms of demand and supply in order to establish a common price for certificates with the ultimate goal to reduce overall emissions among participating countries.

Giving its main aim of emission reduction, many studies sought to evaluate the impact of the EU ETS on emission abatement. Thereby and given data availability, these works, i.e. Ellerman and Buchner (2008) and Anderson and Di Maria (2010), used Business-As-Usual (BAU) Counterfactuals in order to estimate the policy's impact on emissions. However, the EU ETS went through times of major economic distress culminating in the global economic recession

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[1] Since the 01.01. 2012, the commercial aviation sector forms part of industries subject to the policy as well.

2008/2009, hence, any estimate trying to capture abatement due to the trading system have to take these external factors into account.

In this light, Chapter 2 **"Emissions Abatement: Untangling the Impacts of the EU ETS and the Economic Crisis"** tries to shed light on the question to what extend the policy was responsible for abatement and to what extend external factors, mainly, the economic crisis was accountable for the emission reductions taken place during the first two trading phases from 2008 until 2012. Thereby, and different to previous analyses, I make use of the fact that since its introduction in 2005 emission data for installations subject to the policy are precisely recorded and publically available which allows us to evaluate the EU ETS's abatement not relying on BAU forecasts but on actual historic data.

Respectively, untangling the effects of the EU ETS from those of the economic crisis is the first contribution of this dissertation using historical data. One of our major results is that the trading system could not be identified as the main source of emission abatement. Instead, major emission reductions were due to the economic downturn caused by the economic crisis 2008/2009, hence, showing the limited impact of the EU ETS in its first two trading phases with respect to emission reductions.

One particular strong outcome of the impact of the economic recession was that firms covered by the policy were able to build up a considerable stock of emission allowances since companies covered by the policy were not forced to reduce emissions by means of compliance but reduced emissions due to the overall decline in demand, instead. As mentioned previously, the EU ETS adheres to the principles of demand and supply. The resulting oversupply of certificates seriously hampered the functionality in many ways. One particular way is forgone technological change through the lack of stringency of the policy. As mentioned by Porter and van der Linde (1995) already, market-based regulations can foster technological change. However, as a key element policy stringency is named.

Correspondingly, Chapter 3 **"Policy Stringency under the European Union Emission Trading System and its Impact on Technological Change in the Energy Sector"** addresses the issue of how policy stringency, measured as the oversupply of certificates in the market and as policy changes due to the shifts from phase I to phase II, affected "green" technological change in the EU. Thereby, technological change is approximated by patent applications for climate change mitigation technologies at the European Patent Organization

(EPO). As the lion's share of emissions and patent applications stems from the energy sector, I put special emphasize on this sector. Thus, chapter 3 broadens our understanding of the importance of policy stringency under market-based policies in general and, in particular, for the EU ETS. Second, this chapter offers a first measure of forgone technological change for different certificate supplies and phase designs based on our estimation results. Given the obtained results from the empirical exercise, it seems that policy stringency plays a key role in determining the pace of "green" technological change.

An arising question of this evolution is, how effective these technologies actually are when it comes to climate change target achievement. Or in other words, to which extend CCMTs can contribute to reach major climate policy goals since the answer to this questions puts the results of the third chapter into context. Respectively, the fourth chapter "**Climate Change Mitigation and the Role of Technologic Change: Impact on selected headline targets of Europe's 2020 climate and energy package"** is trying to shed light on the impacts of CCMTs on the goal of a 20% share of renewables in gross final energy consumption and on the goal of a 20% increase in energy efficiency measured in final energy consumption. Given the richness of our data, I can further divide these impacts into several sub-groups. Thereby, the impact of these technologies is presented for energy from renewable sources and in addition for energy from sources such as petrol or gas since these sources are still predominant when it comes to energy production. Second, the effect on final energy consumption is shown for overall consumption and for the transport sector, especially considering, that this sector is responsible for nearly one third of final energy consumption. The separation of impacts suggests that there are differences in the effectiveness of these technologies in the way in which they influence the different policy goals, hence, calling for distinct policy actions.

Summarizing, the present dissertation follows a clear and concise narrative, whereby every consecutive chapter addresses upcoming research questions resulting from previous chapters' analyses, having as starting point the separation of GHG emissions under the EU ETS. The remainder is organized as the following. Chapters 2, 3, and 4 are presented where an in-depth discussion of the above introduced topics is taken place along with the actual empirical exercises. Lastly, Chapter 5 concludes with a presentation of the main results and main policy recommendations in order to tackle policy shortcomings and to help to assure major climate policy goals are met.

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Chapter 2: Emissions Abatement: Untangling the Impacts of the EU ETS and the Economic Crisis

1. Introduction

The impact of climate change is today well known, as is its principal cause, the emissions of manmade greenhouse gases (GHG). Indeed, this causality has been acknowledged by several national governments and various treaties have been signed to counter the trend. To achieve these goals, the EU Emissions Trading System (EU ETS) was launched to cut the costs of GHG emissions by relying on market mechanisms. Since its introduction the policy has developed considerably, experiencing a number of turbulent phases as well as the impact of the 2008/09 economic crisis. Undoubtedly, the economic downturn has also affected GHG emissions. However, it is unclear how great this impact has been and what share of the reduction in emissions can be attributed to the EU ETS and what share can be attributed to the economic crisis. Untangling the effects of the EU ETS from those of the economic crisis on emissions abatement is the first contribution made by this paper.

With this objective in mind, this study adopts a panel data approach to untangle the respective impacts. What distinguishes this paper from previous studies is that, instead of relying on estimated emission data, we use the verified emission data reported by each installation under the policy. As such our results are not dependent on forecasts that are subject to a certain degree of uncertainty but rather are based on actual historic data.

The study is organized as follows. First, we describe the EU's system for trading emissions and review the literature dealing with its impact on emission reduction. We then present the data used in the regression, along with an overview of GHG emissions. This section is followed by an outline of the model's specifications and the estimation technique. We then present and discuss our results. Finally, we draw the main conclusions and identify the primary policy implications for the EU ETS.

2. Policy description

The EU ETS was officially launched in 2005. It was the first and largest market-based regulation mechanism to reduce GHG emissions and can be considered the "flagship" policy of the European Commission (EC) in its fight against climate change. To date, it operates in the 28 member states of the EU, plus Lichtenstein, Norway, and Iceland. The main principle of the EU ETS is "cap and trade", where cap refers to an EU-wide cap for GHG emissions set by the EC that is progressively reduced each monitoring period. Companies under the cap are required to cover their emissions with EU emission allowances (EUAs), which are handed out free of charge or auctioned. EUAs, however, can be traded among facilities or countries enabling those that run short of allowances to purchase additional EUAs and so avoid penalization in the event of non-submission. More specifically, installations subject to the policy have to surrender one allowance for every ton of CO_2 that they emit; otherwise, they are subject to heavy fines.

Currently, over 11,000 installations are covered by the policy, accounting for around 45% of the participating countries' total GHG emissions (European Commission 2013). Since the main aim of the policy is to cut industrial GHG emissions only the major emitting sectors (including, oil refineries, steel works and producers of iron, aluminum, metals, cements, lime, glass, ceramics, pulps, cardboards, acids, and bulk organic chemicals) and the energy sector are subject to the policy. However, energy production and electricity/heat production account for the lion's share of GHG emissions at around 32% of the EU-27's total GHG emissions (European Environment Agency n.d.).

EUAs are distributed by auctioning or are handed out for free. In the first two phases of the EU ETS (2005-2012) EUAs were typically given away for free with just a small number being auctioned off; however, today auctioning has become the default method for allocating allowances. This applies particularly to the power generation sector,[2] which from 2013 on is required to buy all of its allowances, because previously the sector was able to pass on its emission costs to final consumers despite receiving allowances for free creating windfall profits (Fabra and Reguant, 2014; Point Carbon 2008). In other sectors, such as manufacturing, the number of free allowances has been reduced gradually from a free-of-charge share of 80% in 2013 to a scheduled 30% in 2020. Allowances that are not given away for free are auctioned at the European Energy Exchange (EEX) or ICE Futures Europe (ICE) which serves as the United Kingdom's platform.

Since its launch in 2005, the EU ETS has gone through a number of changes each marking the beginning of a new phase in EU policy. The first phase of the

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[2] Under Article 10c of the revised EU ETS Directive Bulgaria, Cyprus, the Czech Republic, Estonia, Hungary, Lithuania, Poland, and Romania can hand out a certain number of their EUAs free of charge through to 2020, albeit in a progressively decreasing manner.

EU ETS (2005-2007) was a pilot period of "learning by doing" (The European Commission 2014). The main achievements during this phase were the creation of an EU-wide database recording GHG emissions from all participating installations. This was essential for calculating the number of EUAs to be handed out free of charge in the following phase. Given the absence of reliable emission data prior to 2005, the initial emissions cap and the corresponding amount of allowances were based on historical emission data (Georgiev et al. 2011). However, emission forecasts greatly exceeded actual emissions, which resulted in an oversupply of EUAs and meant that in 2007 the price of the EUAs fell to zero (Griffin 2009).

In the second phase (2008-2012) the EU ETS underwent several changes. First of all, Lichtenstein, Norway, and Iceland joined the system increasing the number of participants to 30[3]. The cap was tightened by 6.5% with respect to 2005 to counter the price deterioration while EUAs from the first phase could not be transferred to the second, thus tackling the same problem. Moreover, a certain proportion of EUAs (around 10%) were auctioned off among the installations. From 2008 onwards, the policy adhered to the goals set by the Kyoto Protocol, namely, cutting its 1990 levels of GHG emissions by 8% in the period through to 2012. However, designed as it is to cut GHG emissions, the EU ETS was strongly influenced by the economic crisis that began in late 2008. The crisis led to an oversupply of EUAs and a fall in their price (see below for a more detailed discussion).

The EU ETS is currently in its third phase (2012-2020), characterized by even more radical policy changes than was the case in the transition from phase I to II. In the third phase a single EU-wide cap has been set as opposed to national caps. As discussed above, the number of allowances being auctioned has increased sharply. Finally, the cap on emissions is reduced annually by 1.74% so as to achieve an emission abatement of 21% in 2020 compared to 2005 level.

3. Literature Review

The literature discussing the EU ETS examines many facets, including evaluations of investment incentives in low-carbon technology (Martin et al. 2011; Rogge et al. 2010), competitive analyses (Graichen et al. 2009), and appraisals of its impact on profits and product prices (Point Carbon 2008; Sijm

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[3] Romania and Bulgaria joined the EU ETS on accession to the EU in 2007

et al. 2006). Several studies also evaluate its impact on GHG abatement and, given that this is the specific focus of the present study, only papers dealing with this question are discussed in detail below.

One of the first attempts at evaluating the effectiveness of the EU ETS in reducing GHG emissions was conducted by Ellerman and Buchner (2008). The authors artificially create a counterfactual (hypothetical emissions without the EU ETS) and compare these emissions to real emissions from sectors under the policy. They do this by using emissions from 2002 as a baseline and projecting these figures through to 2006 taking into account such factors as real GDP growth, energy intensity of the EU economy and single sectors, energy prices and the carbon intensity. The authors conclude that emissions were reduced by 130-200 megatons (MgT) in 2005 and by 140-220 MgT in 2006 by the EU ETS.

Anderson and Di Maria (2010) also seek to identify the abatement achieved by the EU ETS. In line with Ellerman and Buchner (2008), the authors forecast business-as-usual (BAU) emissions, and compare forecasts with observed emissions from participating installations for the first phase of the EU ETS. However, their approach differs from that adopted by Ellerman and Buchner as they estimate BAU-emissions using a dynamic panel approach with the baseline emission data being taken from Eurostat and matched to the participating sectors of the EU ETS. By comparing BAU-emissions to real data for the first phase, the authors estimate a GHG abatement of 247 MgT and, moreover, a year-on-year decrease in the rate of abatement.

The two studies reviewed above only examine the first phase (2005-2007) of the EU ETS. Georgiev et al. (2011), however, extend Ellerman and Buchner's (2008) approach to the first two years of the second phase (2008-2009). The main difference is that they use emissions from the first phase of the EU ETS as a baseline; specifically, they draw on the first three years of the policy as BAU-conditions for the forecast. But, as discussed in Georgiev et al. (2011), the resulting projection and, hence, the GHG abatement should be treated with caution given that the number of observations in the projection is insufficient to be robust and, moreover, they question the reliability of the BAU conditions owing to the impact of the 2008/09 economic crisis.

As the three studies discussed above evaluate the EU ETS before the 2008/09 economic crisis or by employing BAU-conditions that do not capture the impact of the latter, their results fail to account for the major economic changes experienced by the EU and obvious impacts on GHG emissions. Accordingly, the BAU conditions for the emission projections need to be adjusted to ensure forecast reliability.

Taking the influence of the economic recession into account, Declercq et al. (2011) set up a counterfactual scenario by forecasting the GHG emissions for the power sector to determine 2008 and 2009 abatement under the EU ETS. As determinants they consider the demand for electricity, the CO_2 price, and fuel prices. The estimated effect of the economic downturn results in an abatement of 150 MgT of CO_2 for the power sector over the years 2008 and 2009, with the reduction in demand for electricity accounting for a major share of abatement.

The most striking characteristic of any evaluation of the literature assessing the EU ETS and its effect on GHG emissions is that nearly all the studies[4] create counterfactuals artificially using BAU forecasts. As Ellerman and Buchner (2008) point out, there are "better and worse" estimates for the counterfactual, but ultimately the results are obtained from a "what-would-have-been" analysis as the counterfactual can never actually be observed. In contrast to the evaluations reviewed above, the analysis reported here uses historical data to evaluate the impact of the EU ETS and of the economic crisis on emissions reduction. We exploit the fact that, since its introduction in 2005, the EU ETS has developed considerably and that a good body of ex-post data is now available. In this respect, and to the best of our knowledge, this study is the first attempt to analyze the performance of the EU ETS in emission reductions based on ex-post historical data and to account for the effects of the 2008/09 economic crisis.

4. Data and Sources

The original data sample used in this analysis includes 30 countries and covers a time span from 2005 to 2012. With the exception of Norway, Lichtenstein, and Iceland, all countries in the EU ETS belong to the European Union. However, a full data set is only available for 25 countries, since Bulgaria and Romania did not join the EU and become participants in the EU ETS until

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[4] One exception is the firm-level research conducted by Abrell et al. (2011). To assess the impact of the EU ETS on emissions at the firm level the study uses panel data from more than 2000 participating firms for the years 2005-2008. However, the study was conducted before the economic crisis and so does not assess the effect of the recession on CO_2 emissions.

2007[5]; hence, reliable emission data are only available from 2007 onwards. Likewise, Norway, Lichtenstein, and Iceland did not become members of the EU ETS until 2008 and so data are only available for the second phase of the policy. Thus, our eventual sample includes data representing the EU 25 (that is, the EU 28 minus Bulgaria, Rumania and Croatia).

The data sources for this study are Eurostat, the Community Independent Transaction Log (CITL), World Bank Open Data, and BP Statistics. Prices for crude oil and coal have been extracted from the latter two data bases, whereas verified emissions of all national stations under the regulatory system have been extracted from the CITL. All other data were extracted from Eurostat. Table 1 provides an initial description of the evolution in the GHG emissions of the EU 25 countries and the impact of the economic crisis.

Total GHG abatement is calculated as the difference between the 2005 and 2012 emissions. Accordingly, there was an average reduction of 11.778 MgT of GHG emissions per country during the observation period, equivalent to an average percentage reduction of 14.21% for each member state. The most striking revelation however is the impact of the economic downturn on GHG emissions, with an average reduction per country of 10.174 MgT of GHG emissions in sectors under the EU ETS between 2008 and 2009; that is a reduction of 10.48%. Yet, percentage changes as high as 23.36% were also observed. This reduction, achieved in just one year, is equivalent to 86.38% of the total GHG abatement achieved in the first and second phase of the EU ETS. Subsequently, most countries in the EU 25 experienced an economic upturn that led to a recovery in the GHG emission rates in the following year. The last column in Table 1 illustrates this by reporting a negative average abatement of -5.66% for 2010; in other words, an increase in emissions.

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[5] Croatia has only been an official member of the EU ETS since 2013 and so no emission data are yet available.

Table 1: GHG Emissions Overview

Country	Total Change in GHG Emissions (Abatement) 2005-2012 in MgT	Total Abatement 2005-2012 (in %)	Change in GHG Emissions (Abatement) 2008-2009 in MgT	Abatement 2008-2009 (in %)	Abat. 08-09 / Total Abat. (in %)	Change in GHG Emissions (Abatement) 2009-2010 in MgT	Abatement 2009-2010 (in %)
Austria	-4.986095	14.94%	-4.719141	14.71%	94.65%	3.559878	-13.01%
Belgium	-12.356252	22.32%	-9.255089	16.69%	74.90%	3.897041	-8.43%
Cyprus	-0.694979	13.68%	-0.215013	3.86%	30.94%	-0.305413	5.70%
Czech Rep.	-13.138166	15.93%	-6.614269	8.23%	50.34%	1.799522	-2.44%
Denmark	-8.290168	31.31%	-1.087439	4.10%	13.12%	-0.194762	0.76%
Estonia	0.922055	-7.31%	-3.162545	23.36%	342.99%	4.136044	-39.85%
Finland	-3.60174	10.88%	-1.809195	5.00%	50.23%	6.943508	-20.21%
France	-27.63695	21.05%	-13.037252	10.50%	47.17%	4.478226	-4.03%
Germany	-22.465655	4.73%	-44.559032	9.42%	198.34%	26.570097	-6.20%
Greece	-9.827367	13.79%	-6.192321	8.86%	63.01%	-3.721576	5.85%
Hungary	-4.898679	18.72%	-4.835351	17.75%	98.71%	0.590452	-2.64%
Ireland	-5.545017	24.71%	-3.166499	15.54%	57.11%	0.15779	-0.92%
Italy	-46.895929	20.75%	-35.794723	16.22%	76.33%	6.607937	-3.57%
Latvia	-0.114479	4.01%	-0.253113	9.23%	221.10%	0.750367	-30.14%
Lithuania	-46.895929	20.75%	-35.794723	16.22%	76.33%	6.607937	-3.57%
Luxembourg	-0.613812	23.58%	0.082799	-3.94%	-13.49%	0.070968	-3.25%
Malta	0.081172	-4.12%	-0.121472	6.02%	149.65%	-0.018806	0.99%
Netherlands	-3.92537	4.89%	-2.479882	2.97%	63.18%	3.704899	-4.57%
Poland	-6.513296	3.21%	-12.93317	6.34%	198.57%	8.552658	-4.47%
Portugal	-11.18151	30.70%	-1.64968	5.52%	14.75%	-4.09477	14.49%
Slovakia	-4.298866	17.04%	-3.741497	14.77%	87.03%	0.103416	-0.48%
Slovenia	-1.109958	12.73%	-0.793082	8.95%	71.45%	0.06284	-0.78%
Spain	-47.992625	26.14%	-26.526546	16.23%	55.27%	-15.452293	11.28%
Sweden	-1.209659	6.24%	-2.588651	12.89%	214.00%	5.169326	-29.55%
U.K.	-11.271546	4.65%	-33.119481	12.50%	293.83%	5.397695	-2.33%
Total (MgT)	-294.46082		-254.36636			65.372981	
EU25 Average (MgT)	-11.778433	14.21%	-10.174654	10.48%	86.38%	2.61491924	-5.66%

Source: CITL and own calculations

However, this ‘rebound’ in GHG emissions is much lower than the impact of the 2009 economic crisis, suggesting that the economic downturn continued to have an impact on emissions after 2009. This is particularly true of countries such as Portugal and Spain that continued to present reduced rates in 2010.

Unsurprisingly, the reduction in emissions not directly attributable to the EU ETS led to an oversupply of emissions certificates, which are at the heart of the efficient operation of the EU ETS (see below for a more detailed discussion). Yet, the above calculation fails to untangle the impact of the EU ETS on emissions and only reveals that emissions suffered a strong external shock (the economic crisis). Clearly, any regression that seeks to capture the effect of the policy needs to bear this shock in mind.

5. Empirical Strategy

In line with the above reasoning we present the following regression equation. The model specification is inspired primarily by Anderson and Di Maria (2010), who use a flow adjustment model to forecast changes in the emission abatement. In our model the dependent variables are formed by a lagged variable, consumption of energy commodities such as electricity, gas, and coal (or, alternatively, prices), and other explanatory variables. Hence, the EU ETS GHG emissions can be estimated with the following four equations, where the first two are using the consumption of commodities once with GDP growth rates once with a dummy variable for the economic crisis, and the latter two the respective prices including again once GDP growth rates and once the dummy variable. Next we display the four equations.

Consumption Equations[6]:

$$CO2_{i,t} = \beta_0 + \beta_1 CO2_{i,t-1} + \beta_2 nace\_d_{i,t} + \beta_3 c\_gas_{i,t} + \beta_4 c\_coal_{i,t} + \beta_5 c\_elec_{i,t} + \beta_6 GDP\_growth_{i,t} + \beta_7 policy_{i,t} + \varepsilon_{i,t} \quad (1)$$

$$CO2_{i,t} = \beta_0 + \beta_1 CO2_{i,t-1} + \beta_2 nace\_d_{i,t} + \beta_3 c\_gas_{i,t} + \beta_4 c\_coal_{i,t} + \beta_5 c\_elec_{i,t} + \beta_6 crisis_{i,t} + \beta_7 policy_{i,t} + \varepsilon_{i,t} \quad (2)$$

Price Equations:

$$CO2_{i,t} = \beta_0 + \beta_1 CO2_{i,t-1} + \beta_2 nace\_d_{i,t} + \beta_3 gas_{i,t} + \beta_4 coal_{i,t} + \beta_5 elec_{i,t} + \beta_6 GDP\_growth_{i,t} + \beta_7 policy_{i,t} + \varepsilon_{i,t} \quad (3)$$

$$CO2_{i,t} = \beta_0 + \beta_1 CO2_{i,t-1} + \beta_2 nace\_d_{i,t} + \beta_3 gas_{i,t} + \beta_4 coal_{i,t} + \beta_5 elec_{i,t} + \beta_6 crisis_{i,t} + \beta_7 policy_{i,t} + \varepsilon_{i,t} \quad (4)$$

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[6] For reasons of multicollinearity the consumption and price of oil have been excluded from the equations, see also Table A-1.1 and Table A-1.2 in the appendix for further proof.

where the dependent variable *C02* is the GHG emissions taken from CITL, β_0 is the constant in the model, $CO2_{i,t-1}$ are the lagged GHG emissions, *Nace_d* is the economic industry index for the electricity sector, *Gas, Coal,* and *Elec* are the prices for gas, coal, and electricity, respectively, and *C_gas, C_coal,* and *C_elec* are the corresponding consumption of the commodities. The variable *GDP_growth* is the percentage change of GDP on the previous year, whereas *Crisis* is a dummy variable describing periods of economic downturn, used as an alternative way to control for the impact of the economic recession in the model. The variable *Policy* is the difference between the GHG emissions from the ETS and non-ETS sectors to capture the effect of the policy, and $\varepsilon_{i,t}$ is the error term. The subscripts i, t define the cross-section and the time dimensions, respectively. Table 2 displays the descriptive statistics, and table A-2 in appendix contains the full definition of the variables in the model.

As indicated by the regression equations and by the general description of the underlying regression model, the dependent variable is included as a lagged regressor making the model a dynamic one. Accordingly, as suggested in Arellano and Bond (1991), we performed an Arellano-Bond estimation with robust standard errors to correct for potential problems caused by heteroskedasticity. The variables included in the model fulfill different objectives. One of these is to control for the economic activity of the sectors under the EU ETS. Hence, variables accounting for industry specific characteristics are introduced in the model; these can be seen as “classical” control variables. In our model these variables are sector-specific economic activity variables and consumption -alternatively, prices- of energy and fossil fuels.

Table 2: Variables Overview

VARIABLES	Description	Number of Observations	Mean	Standard Deviation	Min	Max
CO2	CO^2 emissions under the EU ETS	200	84.39	107.1	1.878	487.1
nace_d	Industry Index for Electricity Sector	200	98.49	7.367	75.87	118.4
c_gas	Consumption of Natural Gas (Gross Inland Consumption)	200	50,665	114,079	503.3	447,090
c_coal	Consumption of Coal (Gross Inland Consumption)	200	23,503	60,088	0.100	329,723
c_elec	Consumption of Electric Energy (Gross Inland Consumption)	200	9,375	12,092	138.3	45,780
gas	Industrial Consumer Prices for Natural Gas	200	8.537	1.975	2.752	14.43
coal	Coal Prices for north-west Europe	200	92.29	27.92	60.54	147.7
electricity	Industrial Consumer Prices for Electric Energy	200	0.0892	0.0273	0.0409	0.222
GDP_growth	Percentage change of GDP on previous year	200	1.540	4.264	-17.70	11
crisis	Dummy representing the Economic Crisis 08/09	200	0.265	0.442	0	1
policy	Policy Variable to capture the effect of the EU ETS	200	2.016	10.00	-35.35	27.48

Following Anderson and Di Maria (2010), annual production indices are used to model the economic activity of the different sectors under the EU ETS. These indices are given in working days adjusted so as to measure the actual days worked to achieve the output of the observation unit during the observation period (Eurostat 2014b). This index was collected for the main sectors under the EU ETS in line with Eurostat's NACE-classification. These sectors are Mining and Quarrying (NACE B), Manufacturing (NACE C), and Energy (NACE D). All the indices were normalized and 2010 was selected as a baseline and given a value equal to 100. It should be noted that the only economic industry index used in the regression is that of the electricity sector, $nace\_d_{i,t}$. This is because neither the industry index for the manufacturing sector nor that for mining and quarrying contributed to explaining emissions in this study. However, by including electricity consumption in the equation, emissions from the manufacturing sector are indirectly accommodated in the regression since the main cause of emissions stemming from this sector is precisely electricity consumption (International Energy Agency 2007).

As shown by Apergis and Payne (2009) and Chang (2010), there is evidence that energy, gas, and fossil fuel consumption is linked to GHG, mainly CO_2 emissions. Additionally, as discussed earlier in the literature review, Declercq et al. (2011) found that a reduction in electricity demand was the main driver of GHG abatement in the years 2008 and 2009. To account for this fact, data for the electric energy, gas, and coal consumption of the various member states have been extracted, where consumption in each case refers to gross inland consumption. The consumption of all the commodities is measured in thousands of tons of oil equivalent to facilitate data comparison. Alternatively, we use the industrial consumer prices for fossil fuels and electricity to account for the demand of these commodities following the same reasoning as with consumption levels. This is mainly due to the fact that naturally the consumption of a commodity is influenced by its price.

A second objective of the regression equation is to account properly for the effects of the economic crisis. As discussed, the 2008/09 economic crisis had, and in some parts of the EU continues to have, a strong influence on economic performance and, hence, GHG emissions. This means that the analysis needs to control for any market disturbances. In this work two different ways are used to account for the crisis.

The first one is rather simple by introducing annual real GDP growth rates into the regression equation. This measure is well suited to capture the effect of the crisis. For example, all but one[7] countries of the EU 25 had negative growth rates in 2009 resulting as an effect of the economic downturn.

The second way how the economic crisis is modeled in this work is by creating a dummy variable that takes a value of 1 if a country shows a negative annual GDP growth rate and 0 otherwise. In this way, on 53 occasions the variable

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[7] The exception is Poland which had an annual growth rate of 1.6% in 2009 according to Eurostat.

takes the value 1 and on 147 the value 0. This definition has the additional advantage that the coefficient can be interpreted as the CO_2 abatement attributable to periods of economic downturn, thus facilitating our untangling of the respective impacts of the ETS policy and the recession.

A third objective for introducing a variable into the equation is to capture the effect of the EU ETS on GHG emissions. In the above regression, the variable $policy$ is designed for this purpose. This policy variable in general has to fulfill two objectives: first, it has to capture the impact of a policy on outcomes and, second, it should cancel out all other influences on outcomes. In this instance, the policy variable should only capture the abatement of GHG emissions due to the EU ETS and not those due to other influences.

Thus, the policy variable was created as follows. Given that GHG emissions across different sectors suffer the same external shocks, a comparison of GHG emissions from sectors under the EU ETS and those from sectors not covered by the policy should enable us to capture nothing but the effect of the EU ETS. Fortunately, this comparison is feasible because Eurostat provides emissions data for sectors that do not form part of the trading system. These data include emissions from road transport, building, agriculture, and the waste sector. Emissions produced by land use, land use change and forestry, international shipping, and international aviation are not, however, included in the data. Thus, non-ETS emissions are calculated as the difference between total GHG emissions and verified emissions under the ETS (Eurostat 2014a). To make the data for non-ETS and ETS sectors comparable, data were first standardized with 2005 emissions representing the baseline year and given a value of 100. In a subsequent step the standardized emissions from the ETS were subtracted from the emissions of the non-ETS sectors. Accordingly, the resulting measure shows the different evolution taken by GHG emissions and, supposing similar trends in emissions, these differences can be interpreted as the impact of the EU ETS.

However, to constitute a valid measure for capturing the impact of the policy on emission abatement the validity of this transformation has to be tested. In a first step it should be possible to check if the policy variable actually captures an emission reduction attributable to the ETS. In this regard the differences between emissions emanating from ETS and non-ETS sectors should be positive, assuming that is that the policy has a negative impact on emissions. As the figures in Table 3 show, the design of the policy variable captures this assumption since over 60% of the observations of the variable "policy" are positive as is its mean.

Table 3: Descriptive data for the variable policy

Variable	Obs	Mean	# of positive values	% of pos. values	# of negative values	% of neg. values
Policy	200	2.0158	125	62.5	75	37.5

Yet this is insufficient to provide robust proof of the validity of the policy variable. In a second step, we tested whether emissions from sectors under the EU ETS present similar trends to those emanating from non-ETS sectors. In other words, we sought to determine whether the external effects have similar impacts on emissions emanating from the two sectors so that a comparison of their respective emissions might be deemed valid. In so doing we performed two auxiliary regressions to determine whether similar emission trends might be assumed (Table 4). The first regression (column "co2_nonets_stand") estimates the effect of the crisis on emissions from sectors not forming part of the EU ETS.[8] The second regression (column "co2_stand") estimates the effect of the crisis on emissions from sectors under the EU ETS and so takes into account the impact of the policy on these emissions. By comparing the coefficients of the variable "crisis" in the two regressions we are able to verify whether emissions emanating from the two sectors behave similarly or not.

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[8] As pointed out by a referee, non EU ETS sectors are more heterogeneous than those sectors that are included in the EU ETS, but we can no further refine our analysis here because of lack of available data. However, this does not affect our results and the subsequent computations.

Table 4: Auxiliary Regression using Cluster Robust Standard Errors

	(1)	(2)
VARIABLES	co2_nonets_stand	co2_stand
Crisis	-3.328***	-3.959***
	(0.660)	(0.929)
Policy		-0.899***
		(0.108)
Constant	97.99***	97.95***
	(0.175)	(0.186)
Observations	200	200
R-squared	0.084	0.731
Number of country	25	25

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The comparison is then completed by calculating the ratio of the two coefficients of the variable “crisis”, where a value equal to 1 means that the impact of the economic crisis on the different rates of emission is the same. Here we obtained a ratio of 0.841, which can be considered as evidence that external effects have a similar impact on the respective rates of emission and, so, we can assume the policy variable to be valid. However, the effect of the crisis on emissions emanating from the EU ETS is slightly greater than that on emissions outside the trading system which could create a possible upward bias[9] in the effect of the policy.

Finally, we turn our attention to the dependent variable, namely, GHG emissions under the EU ETS. As discussed above, annual GHG emissions are reported by CITL. Overall, more than 11,000 heavy emitting installations in the power generation sector and from manufacturing industry are obliged to report to this authority under the EU ETS. GHG emissions are given in tons of CO_2 equivalents, since in addition to the emission of CO_2 other gases such as nitrous oxide, used in the production of acids (European Commission 2013) and perfluorocarbons (PFCs), resulting from aluminum production, are covered by

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[9] The comparison of emissions emanating from non-ETS sectors and sectors under the EU ETS might be considered in terms of substitution effects, which would result in a bias in the creation of the policy variable. However, these effects would only become manifest in the long-run and, accordingly, do not affect the policy variable here.

the policy. CO_2 equivalent in this sense refers to the amount of CO_2 emissions that is equal to the global warming potential of the emission, for example, of one tone of nitrous oxide.

6. Results

In line with the strategy outlined above, we performed five different estimations for each case (using once consumption of commodities and once the respective prices) (Table 5 and 6). In each of the cases, the first three estimations (Est.1, Est.2, Est.3) omit either the variable accounting for the impact of the economic crisis or the variable designed to capture the effect of the EU ETS on GHG emissions (*GDP Growth*, *Crisis*, and *Policy*, respectively). In estimations four and five (Est.4 and Est.5) the policy variable is introduced jointly with one of the variables controlling for the impact of the economic crisis; hence, once *Policy* with *GDP Growth* and once *Policy* with the dummy variable *Crisis*. This procedure allows us to make two important observations. First, we are able to verify whether the ETS policy or the economic crisis was primarily responsible for the reduction in GHG emissions and, second, we can narrow the range of abatement shares attributable respectively to the policy and the economic crisis. The overall fit of the different specifications can be stated since the Wald-Test strongly rejects the H_0 of jointly statistical insignificance of the covariates.

The significance of the lagged endogenous variable throughout the different specifications is consistent with the available evidence in the literature (Anderson and Di Maria 2010; Kamerschen and Porter 2004); however, its magnitude is somewhat smaller. The economic activity index for the electricity sector regarding the 'consumption' regressions (Table 5 above) shows significance only in the first two estimations (Est.1 and Est.2), whereas it loses its statistical significance for the remaining. Regarding the "price" regressions, the economic activity index is significant in all estimations. Concerning its sign, it appears to follow the expected trend, as it shows that the higher the activity of the electricity sector, the higher are GHG emissions. The signs for gas consumption and gas price are the expected, but the coefficients lack statistical significance. The same happens for coal consumption coefficients and signs. The electricity consumption/price estimate presents highly significant values (1%) across the different specifications. This points to a clearly positive influence on rates of emission and its magnitude does not vary significantly over the ten equations. This effect is in line with the theory described above in the literature review.

Table 5: Robust Arellano-Bond Estimation using Consumption

	(1)	(2)	(3)	(4)	(5)
	Est.1	Est.2	Est.3	Est.4	Est.5
Variables	CO2	CO2	CO2	CO2	CO2
L.CO2	0.598***	0.596***	0.560***	0.587***	0.585***
	(0.0634)	(0.0641)	(0.0611)	(0.0668)	(0.0659)
nace_d	0.141**	0.196***	0.131	0.0620	0.0944
	(0.0598)	(0.0674)	(0.101)	(0.0731)	(0.0873)
c_gas	-4.11e-05	-3.86e-05	3.55e-06	-2.69e-05	-2.23e-05
	(3.52e-05)	(3.27e-05)	(3.36e-05)	(3.65e-05)	(3.70e-05)
c_coal	0.000366	0.000368	0.000366	0.000334	0.000328
	(0.000396)	(0.000403)	(0.000376)	(0.000376)	(0.000378)
c_elec	0.0109***	0.0112***	0.0116***	0.0108***	0.0111***
	(0.00299)	(0.00309)	(0.00308)	(0.00298)	(0.00305)
GDP_growth	0.462**			0.409	
	(0.234)			(0.257)	
Crisis		-2.829**			-2.477*
		(1.304)			(1.350)
Policy			-0.198**	-0.143	-0.166**
			(0.0822)	(0.0879)	(0.0798)
Constant	-90.26***	-97.61***	-94.40***	-80.71***	-85.29***
	(29.08)	(29.67)	(30.85)	(29.35)	(30.06)
Observations	150	150	150	150	150
Number of country	25	25	25	25	25
chi2 of the Wald-Test	728.7	644.5	364.9	594.1	552.7
m1^	-2.558	-2.507	-2.438	-2.600	-2.479
m2^	0.743	0.652	0.622	0.583	0.450

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

^ Note: m1 and m2 are, respectively, the z-Value of the Arellano-Bond Test for first- and second-order autocorrelation

Table 6: Robust Arellano-Bond Estimation using Prices

VARIABLES	(1) Est.1 CO2	(2) Est. 2 CO2	(3) Est. 3 CO2	(4) Est.4 CO2	(5) Est. 5 CO2
L.CO2	0.575***	0.573***	0.500***	0.556***	0.555***
	(0.0689)	(0.0692)	(0.0729)	(0.0724)	(0.0705)
nace_d	0.334***	0.377***	0.302**	0.203**	0.225**
	(0.122)	(0.120)	(0.129)	(0.102)	(0.109)
Electricity	-122.2**	-146.7***	-194.3***	-134.9**	-155.5***
	(50.94)	(52.81)	(72.36)	(53.96)	(54.64)
Gas	0.704	0.603	0.588	0.869*	0.803
	(0.518)	(0.522)	(0.510)	(0.488)	(0.496)
Coal	0.000364	0.00721	0.0208**	-0.00124	0.00382
	(0.0121)	(0.0152)	(0.00971)	(0.0119)	(0.0149)
GDP_growth	0.679***			0.585**	
	(0.262)			(0.275)	
Crisis		-5.087***			-4.465**
		(1.849)			(1.825)
Policy			-0.309**	-0.234*	-0.252**
			(0.140)	(0.132)	(0.123)
Constant	5.889	6.786	22.74	20.92	22.97
	(11.98)	(12.40)	(15.04)	(13.91)	(14.55)
Observations	150	150	150	150	150
Number of country	25	25	25	25	25
chi2 of the Wald-Test	178.1	187.1	180.5	177.0	193.3
m1^	-2.114	-2.158	-2.063	-2.080	-2.080
m2^	-0.243	-0.238	-0.443	-0.338	-0.359

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

^Note: m1, respectively, m2 is the z-Value of the Arellano-Bond Test for first- and-second order autocorrelation

6.1 Drivers of GHG emissions abatement and the effect of the EU ETS

In a first step of our empirical analysis, we are interested to observe how GHG emissions are influenced by the economic crisis and by the EU ETS if the variables accounting for both are introduced separately. Accordingly, we first introduced in Est.1 and Est.2 (Tables 5 and 6 above) the variables *GDP Growth* and *Crisis*. In both models, the coefficients of the two variables describing the influence of economic performance are statistically significant at 5% and show the expected relationship. This means that higher GDP growth rates lead to higher emissions and, vice versa, an economic downturn comes in hand with an emission reduction which leads us to conclude that the economic downturn among the EU 25 was a main driver of the reduction in emission rates.

In Est.3, in contrast to Est.1 and Est.2, we focus on the impact of the policy on emissions. The impact is clearly negative and statistically significant. Viewed separately, both the policy and the crisis played a major role in cutting emissions. However, when both variables are introduced jointly into the two models we obtain somehow different results. Results in Est.4 in the consumption model (Table 5 above) show that none of the two variables are statistically significant.[10] On the contrary, when we introduce the variable *Policy* and *Crisis* jointly results become significant: As can be seen in Est.5 of Table 5, both the dummy for the economic crisis (at 10%) and the policy variable (at 5%) are statistically significant and have a negative impact on GHG emissions.

For the model using prices for commodities (instead of consumption), the regression including *GDP Growth* and *Policy* (Est.4; Table 6) shows for both variables statistical significance, and the expected signs. In estimation 5 we use *Crisis* and *Policy*, and both variables show statistical significant, this time at 5%, and have a clear negative impact on GHG emissions. Additionally, the fact that the variables accounting for the economic crisis and the policy variables present smaller absolute values when introduced jointly (across all regressions) means that they absorbed reduction-shares of each other when considered alone. These results suggest that the policy variable absorbed a considerable amount of economic activity in Est.3 in both models. Hence, an interpretation of the impact of the policy without taking into account the effects of the economic downturn would be misleading, in the sense that this might result in an overestimation of the effectiveness of the EU ETS in its ability to reduce emissions.

The way in which the policy variable has been constructed here does not allow us to provide a direct interpretation of its coefficient. However, there is an alternative way in which the effect of the EU ETS on GHG emissions might be disentangled: by comparing the coefficients accounting for the economic crisis before and after introducing the policy variable into the equations.

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[10] It is worth noting that in the Non robust estimation both variables (*GDP Growth* and *Policy*) are significant and have the expected signs.

Accordingly, we compared the coefficients of *GDP Growth* and *Crisis* in Est.1 and Est.4, and also in Est.2 and Est.5. To do so we focused on the percentage change in the magnitude of the coefficients from one equation to the other. In the case of the coefficient of *GDP Growth* this percentage change is equivalent to an 11.47%[11] reduction for the 'consumption' model and 13.84% reduction for the 'price' model following the introduction of the policy variable into Est.4. If we repeat this exercise for the dummy variable *Crisis*, the corresponding reductions are 12.44% for the consumption case, and 12.22% for the model using prices. This result suggests that the coefficients of the economic crisis variable in Est.1 and 2 capture something in addition to the effect of the crisis, namely, the impact of the EU ETS on emission abatement.

By approaching the problem of untangling the abatement effect of the policy in this way, the impact of the EU ETS can be considered as being in between 11.47% and 13.84% of the total GHG emission reduction during the observation period. We started our analysis with the less statistically significant estimates, hence, regressions using *GDP Growth* and *Policy* jointly in the 'consumption' model, until we reached our favored model, the one that uses *Crisis* and *Policy* simultaneously in the equation with prices. Interestingly, regardless which model was used and which variable accounted for the economic crisis, similar results were obtained. Table 7 summarizes the results from the different approaches presented.

Table 7: Results Overview

	Models			
	Model using Quantities		Model using Prices	
	crisis	GDP_growth	crisis	GDP_growth
(1) Percentage due to the EU ETS	12.44%	11.47%	12.22%	13.84%
(2) Total Abatement for the EU-25 due to the EU ETS (MgT)	36.638	33.780	36.009	40.759
(3) Average abatement for the EU- 25 due to the EU ETS (MgT)	1.466	1.351	1.440	1.630

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[11] For this specific case, the calculation is not based on statistical significant values. We include it for completeness.

6.2 *Robustness and validity of the estimates*

Having estimated the impact of the crisis and the EU ETS on GHG emissions, we now need to test the robustness of these estimates to guarantee their validity. Problems might well arise if there are any structural breaks in our sample of 25 countries over the eight-year period. For this motive, two different Chow tests were performed. The first of these was designed to capture a structural break between countries, namely, between the EU 15 and its extension east in 2004 when ten new member states joined the EU. The second was designed to capture any structural break in the time dimension, more specifically, if there was any break in the transition from the first to the second phases of the EU ETS. Both tests showed there to be no structural breaks in either the time dimension or the cross-sections, suggesting that the sample can be estimated as a whole and does not have to be split (Statistical test results available upon request).

Furthermore, an Arellano-Bond test for model misspecification has been performed. In a first step of the test we are interested in identifying first-order serial correlation caused by the inclusion of the dependent variable lagged once. Therefore, first-order serial correlation in the first differenced errors is expected. In a second step we are eager to control for second-order serial correlation in the first differenced errors. If there would be any we have to conclude that the moment conditions of the instruments are not valid. Accordingly, this would mean a misspecification of our model. As can be seen at the m1-values in table 5 and 6 for the first step we reject the H_0 of zero autocorrelation in the first-differenced errors of order one, as expected. However, we do not reject the H_0 for second-order zero autocorrelation. This concludes that our model is correctly specified and moment conditions are valid. Furthermore, robust standard errors have been used to correct for any problems caused by heteroscedasticity.

Turning our attention to the validity of our estimates, only a few studies empirically tried to quantify this effect of the economic recession on emissions. One of these is the work by Declercq et al. (2011). Recall that the authors estimated 150-MgT abatement for the European power sector due to the impact of the economic crisis. However, this study just focuses on the impact on the electricity sector and not on the whole EU ETS sector. In order to compare our results some adjustments had to be made. First of all, we subtracted the emission abatement estimated share of the EU ETS from the total emission abatement from 2005-2012 [294.46 MgT (Table 1) – 36.01 MgT (Table 7)]. As a result, we obtained the share of emissions abatement that cannot be attributed to the EU ETS, which is 258.45 MgT.[12] Then we multiplied by the electricity sector's share of GHG emissions (≈0.71). Thereby, we obtain 183.5 MgT of emission reduction for the electricity sector that cannot be attributed to the EU ETS.

A comparison of these outcomes with those reported by Declercq et al. (2011) reveals a close similarity, providing further validation for the estimates reported here. Especially when having in mind that the economic crisis was not yet overcome by the year 2009, which was the analytical time frame in Declercq et al. (2011). Effectively, through the increased time frame of our study and the ongoing nature of the economic crisis in the Euro-zone it is not surprising that our estimates for emissions reduction in the electricity sector exceed those by Declercq et al. (2011).

7. Conclusions

In this paper we have used historical emission data from installations under the EU ETS to evaluate the impact of the policy on GHG emissions during the first two trading phases (2005-2012). According to the results obtained, the total share of emission abatement due to the EU ETS ranges in between 33.78 and 40.76 MgT of the 294.5 MgT of the total reduction recorded by the EU-25 Member States from 2005-2012. This seems to indicate that most of the reduction in emissions is due to the economic recession rather than to the EU ETS. Moreover, the estimated reduction attributable to the EU ETS here is well below the reductions forecast in the pre-crisis literature. In general, the latter studies overestimated the capacity of the EU ETS to reduce GHG emissions. Clearly, the market environment suffered a strong external shock with the economic crisis. This could not be foreseen ex ante, but it changed the BAU-conditions, and these need to be accounted for.

The results presented earlier illustrate the severe impact of the economic downturn on GHG emissions for sectors under the EU ETS. Moreover, the figure of around 255 MgT of emission reduction not attributable to the EU ETS

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[12] This figure is obtained by using the results of estimation with prices when including the Crisis variable. This estimation produces the most significant coefficients for the economic and policy variables. We can make an alternative computation of the emission reduction for the electricity sector that cannot be attributed to the EU ETS: by means of the results of the estimation with prices where we use the GDP_Growth variable. In this case, we obtain a reduction of 180.13 MgT [(294.46-40.759)*0.71], figure which is substantially similar to that obtained before.

has major implications for the successful operation of the system. Given that installations under the EU ETS were able to save a significant number of EUAs thanks to the economic crisis (and not because of their abatement efforts), the market for allowances was oversupplied. The consequences of this are complex, but clearly the price for allowances fell, which reduced participants' incentives to invest in low-carbon technology. Hence, the effectiveness of the EU ETS was seriously compromised.

To counteract these outcomes, the European Commission has delayed the auction of some 900 million EUAs to the latter stages of the third trading period ('back-loading'). However, this action does not mean an overall reduction of the total amount of allowances in the market, but only a shift of further supply of certificates at a later stage. A brief look at the price of EUAs suggests that these actions taken up to now do not adequately address the problems created by the economic crisis, namely the immense certificate oversupply. To tackle the problem of an excess supply of allowances, a more promising approach can be the net reduction of allowances in the market, either by tightening the emission cap even further or by plainly cancelling future allocations. While this type of measures could face opposition from the industry and some policy makers, it appears to be the best way to effectively decrease the amount of permits, so that emissions are further reduced.

All in all, the results obtained in this study provide robust estimates of the magnitude of emission abatement attributable to the EU ETS, and can serve as the basis to increase the effectiveness of the system in its attempts to cut GHG emissions. The main limitation however in evaluating the EU ETS remains the availability of data and the quality of those data. One key feature that would facilitate future evaluations would be for firms under the policy to record, in addition to their emission data, economic performance data. In this way any reduction in GHG emissions could be traced back to their origin more effectively and thus improve the accuracy of estimates. Future research would benefit greatly from the availability of micro-level firm data as this would allow a more precise quantification of the reduction in emissions attributable to the EU ETS.

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Appendix:

Table A-1.1: Collinearity Statistics

Variable	VIF
lag_CO2	3,22
nace_d	1,12
c_oil	35,21
c_gas	1,90
c_coal	2,01
c_elec	33,14
crisis	1,14
policy	1,19
Mean VIF	9,88

Table A-1.2: Collinearity Statistics

Variable	VIF
lag_CO2	1,03
nace_d	1,15
oil	5,35
gas	1,49
coal	4,51
elec	1,21
crisis	1,21
policy	1,22
Mean VIF	2,15

Table A-2: Variable Description and Sources

Variables	**Description**	**Source**
CO2	CO^2 emissions under the EU ETS	CITL
nace_d	Industry Index for Electricity Sector	Eurostat
oil	Oil Prices (WTI)	World Bank Open Data
gas	Industrial Consumer Prices for Natural Gas	Eurostat
coal	Coal Prices for north-west Europe	BP Statistics
electricity	Industrial Consumer Prices for Electric Energy	Eurostat
c_gas	Consumption of Natural Gas (Gross Inland Consumption)	Eurostat
c_coal	Consumption of Coal (Gross Inland Consumption)	Eurostat
c_elec	Consumption of Electric Energy (Gross Inland Consumption)	Eurostat
GDP_growth	Percentage change of GDP on previous year	Eurostat
crisis	Dummy representing the Economic Crisis 08/09	Eurostat/Own Calculations
policy	Policy Variable to capture the effect of the EU ETS	Eurostat/Own Calculations

Chapter 3: Policy Stringency under the European Union Emission Trading System and its Impact on Technological Change in the Energy Sector

1. Introduction

Technological change aimed at mitigating the impact of economic activity on climate change is a powerful tool for moving towards a low-carbon economy. To strike out on this path, various policies have been adopted worldwide. One of these is the European Union Emission Trading System (EU ETS), which as a market-based regulation, established the first and largest market for greenhouse gas (GHG) emissions allowing installations in the system to cut their emissions in a flexible and cost efficient way. However, external shocks and a lack of stringency have led to the creation of a sizeable oversupply of allowances in the market potentially hampering the effect of the policy on low-carbon technological change (Sandbag 2013).

Against this backdrop, the primary goal of our study is to determine empirically whether or not an oversupply of allowances in the market has a negative effect on the innovative behavior of firms covered by the policy and beyond,[13] measured in terms of the number of patent applications filed at the European Patent Office (EPO). And, secondly, how policy changes related to greater stringency affect innovative behavior given policy modifications in the transition from Phase I to Phase II of the EU ETS. For this reason, we employ a count data model to estimate the impact of certificate oversupply on climate change mitigation technologies (CCMTs)[14] as a whole and, especially for technologies related to the energy sector since this sector is the most productive in terms of CCMT patenting. Secondly, and since the EU ETS falls within the category of market-based regulations that are considered well-designed environmental regulation, we seek to validate the "weak" version of the Porter

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[13] In order to measure the innovative activity with respect to "green" technologies, patent counts for CCMTs are used as a proxy. We do not only use patents from firms subject to the policy, but all patent counts of the respective technology field. Hence, our results suggest that not only innovation under the EU ETS is influenced by it, but, as well, innovative activity outside the policy. Thereby, we take into account that innovation does not only take place within firm boundaries subject to the policy, but as well outside (Lee. et al 2009).

[14] Our study is using aggregated patent counts per country. Thereby, we are interested in analyzing and detecting general impacts, such as an oversupply in the certificate market as whole, and the effects of a malfunction of the policy on the overall patenting activity. The corresponding conclusions are broken down to firm-level, because these effects are reflecting firms' behavior.

hypothesis (Porter, 1991; Porter & van der Linde, 1995); that is, we aim to determine whether market-based environmental regulations are a suitable tool to spur “green” innovation.

Therefore, with this study we seek to contribute to the literature by showing how the innovative behavior of firms, especially, energy firms in the EU ETS and outside, measured in terms of patent applications for CCMTs to the EPO on a country level, is affected by the excess supply of EUAs, on the one hand, and by policy changes linked to an increased stringency, on the other. Thereby, given the richness of our data, we pay special attention to technologies for the reduction of GHG related to energy generation, transmission or distribution, as this sector is responsible for the biggest share of GHG emissions under the EU ETS. Our study closes a gap in the literature with regard to the EU ETS, and more broadly for any cap-and-trade regulation. Moreover, it broadens our understanding of the way in which policy failures influence innovative behavior under such policies.

The rest of the study is organized as follows. First, we briefly outline the EU ETS and its different phases and review the literature. In section 3, we describe the structure of the data and the variables used in the empirical exercise. Next, we present the methodology and the regression outcomes which are then and discussed along with their implications for the research questions posed. Finally, we draw our main conclusions and highlight policy measures that might put the EU ETS back on the right track.

2. Description & Aims of the Policy

In 2005 the EU ETS came into operation. The trading system can be considered the European Commission’s (EC) main policy for reaching its ambitious GHG reduction targets under the 2030 framework for climate and energy policies. To date, the 28 EU Member States, as well as the three EEA-EFTA states (Iceland, Liechtenstein, and Norway) have joined the system, making it the world’s largest carbon market. The main principle of the EU ETS can be summed up quite simply as “cap and trade”. The first step in the system – “cap” – sees the EC set an EU-wide ceiling for installations under the policy which is then gradually reduced every monitoring period. The GHG ceiling is fixed in such a way that the EC issues so-called EU emission allowances (EUAs), which represent the right of a holder of such a certificate to emit one ton of CO_2, or an equivalent amount of GHG with respect to its climate impact as listed in Annex II of the EC Directive 2003/87/EC (European Commission 2013).

Hence, in order to reduce the EU ETS cap the EC cuts the overall number of EUAs in the market. Firms subject to this policy have to cover, therefore, their emissions by allowances; otherwise, they face heavy fines for every ton of CO_2 emission not covered. The second step – "trade", on the other hand, permits firms in the case of a shortage of allowances to purchase additional EUAs in a common market and, so, avoid penalization for non-compliance. Furthermore, EU ETS companies have the option of covering some of their emissions using international offsets, the so-called "Kyoto-offsets" (KO), stemming from Clean Development Mechanism or Joint Implementation projects. The principle underpinning the EU ETS is market-based regulation which aims to leave the means of compliance in the hands of the firms.

Currently, more than 11,000 installations are subject to the policy, accounting for around 45% of total GHG emissions in the participating countries. Only heavy-emitting sectors are covered by the policy, [15] which includes many manufacturing industries[16] and the power generation sector. The latter, however, is responsible for the lion's share of GHG emissions, accounting for 31% of total GHG emission from the EU 27 (European Environmental Agency 2012).

The EU ETS has been implemented in three phases, each marked by fundamental changes in policy design. The first phase (2005-07) can be considered a trial phase adhering to a "learning by doing" credo. Given that prior to 2005 no reliable emission data for the sectors in the new system were available, the main task was to build an EU-wide data base for GHG emissions for the participating members. Precisely due to this lack of emission data, the first phase was marked by a certificate oversupply that led to EUAs being priced at zero from mid-2006 on.[17] The default distribution method for the EUAs was that of free allocation in accordance with the national allocation plans. With the second phase (2008-12), the EC sought to improve the EU ETS by cutting total

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[15] From 2012 on, aviation has also been covered by the EU ETS, so that all the participating countries' flights (within, outgoing, and incoming) are subject to the policy.

[16] Manufacturing sectors covered by the EU ETS are oil refineries, steel works and producers of iron, aluminum, metals, cements, lime, glass, ceramics, pulps, cardboards, acids, and bulk organic chemicals.

[17] Nonetheless, a significant impact of the EU ETS first phase on CO_2 emission abatement was found by Ellerman and Buchner (2008).

allowances by around 6.5% compared to the 2005 level. To further counter price corrosion, the EUAs from the first phase were not bankable into the second period, while several participants started to auction off some of their allowances as opposed to just giving them away. These actions served to strengthen the policy in its aim to further cut GHG emissions.

However, the start of the second trading period coincided with the onset of the global economic crisis (2008/09) which had a marked impact on production levels and, hence, on GHG emissions in the participating countries. For this motive, installations in the system reduced their emissions by a sizeable volume as a result of the economic recession rather than their abatement efforts (Bel & Joseph 2015). This in turn led to a build-up of a considerable oversupply of allowances in the market, a problem that was exacerbated by the fact that during this second trading phase firms could cover part of their emissions by KOs. All in all, the stringency of the policy was greatly compromised. This is particularly evident if we consider the marked deterioration in price, falling to 0.16€/CER (Commodity Exchange Bratislava 2015) by 2014, which was equivalent to providing firms with a "free lunch"[18].

The EU ETS is currently in its third phase (2013-2020). A major change with respect to the earlier phases is the introduction of a cap that is reduced each year by 1.74% in an attempt at reaching the emission abatement target of 21% of the 2005 level by 2020. Likewise, the default method for allocating allowances has gradually shifted from a free-of-charge distribution to that of auctioning. The EC has also implemented the "back-loading" of additional allowances, thus postponing the auctioning of 900 million EUAs until 2019-2020 resulting in a reduction of 400 million allowances in 2014, 300 million in 2015, and 200 million in 2016 (European Commission 2014). However, these measures need to prove themselves effective in tightening policy stringency and reducing the oversupply created since 2008 so that the price of EUAs might rise.[19]

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[18] Even though, CERs created by CDMs intensified the built-up of the oversupply under the EU ETS, they fostered international cooperation for the use of renewable energy sources (Tang & Popp 2016).

[19] Since the introduction of the "back-loading" initiative in 2014, the price of EUAs on the secondary market has increased markedly (c. 4.5€/EUA in January 2014 vs. 7.5€/EUA in May 2015). However, the price is subject to considerable volatility and so no clear trend can be identified (European Energy Exchange 2015)

3. Induced technological change and the EU ETS

The main drivers of emission abatement under the EU ETS were, and continue to be, fuel switching and the impact of the global recession that hit the EU in 2008/09. Fuel switching has proved to be a valid tool for cutting emissions in a cost efficient manner, especially in the power generation sector (Delarue et al. 2008). But, as Calel & Dechezleprêtre (2016) point out, fuel switching alone cannot provide sufficient emission abatement to meet the ambitious EU target of an 80-95% reduction in 1990 GHG emission levels by 2050. For this reason, the EC emphasizes that "the Emissions Trading System is the principal driver of the deployment of new technology, by putting a price on carbon emissions, and so stimulating the development of technologies which avoid them" (European Commission 2015). The idea underpinning this statement is the hypothesis known as "induced innovation", which was first proposed by Hicks (1930) and later reformulated in terms of environmental regulation by Porter (1991) and Porter & van der Linde (1995), where it is known as the Porter hypothesis (PH). One version of this hypothesis states that well-designed environmental policies can foster "green" innovations.[20]

Many papers have subsequently sought to provide theoretical as well as empirical validations of the question as to whether environmental regulations *de facto* spur environmental innovation.[21] Few, however, have focused on market-based regulations such as the EU ETS and its strong link to the energy sector. Popp (2003), for example, compared the innovation impact of a market-based regulation on coal-fired electric utilities, on the one hand, and a command-and-control regime, on the other. By focusing on the transition from one policy regime to the other, Popp recorded a surprising finding following the introduction of the 1990 Clean Air Act (CAA) in the US. Contrary to theoretical predictions, the overall number of innovations (as measured by patent counts) did not rise. However, he found that the direction of technological change was altered by the policy. Although the overall number of patents decreased during the observation period, the quality of patents with respect to environmental-friendliness increased. Accordingly, the shift to a market-based regulation

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[20] This is typically referred to as the "weak" version of the PH. The remaining versions identified by Jaffe & Palmer (1997) are the "narrow" and the "strong" version of the PH.

[21] As our study takes an empirical approach to analyze EU ETS –a market-based regulation-, only empirical analyses of such policies are reported here. See Ambec et al. (2013) for a detailed overview of the recent literature in this field. For additional literature on induced innovation, technological change and economic modeling see as well Grübler et al. (2002) and Löschel (2002).

spurred “green” innovation,[22] which could be seen as a favorable outcome of the policy regime change.

Evidence that environmental policies can spur innovation is also to be found in Johnstone et al. (2010). Using the patent counts for 1978 to 2003 for renewable energy sources in 25 countries, the authors demonstrated that different environmental policy regimes have different outcomes with regards to technological innovations. For example, market-based regulations promote technological innovations for renewable energy sources that are in competition with fossil fuels and which are less costly to develop (e.g., wind power as opposed to solar power). This is highly plausible given that market-based regulations leave it up to the company to decide how to meet policy goals. Thus, profit-maximizing firms will tend to choose the path with the least costs in order to comply with the regulation.

With respect to the EU ETS and the energy sector, Rogge and Hoffmann (2010) are presenting a mixed image of policy impacts in an interview-based study of the German electricity sector. On the one hand, the policy was seen to have had an impact on R&D spending and an accelerated employment of carbon capture technologies, especially on large-scale, coal-based power generation; however, due to the lack of stringency and predictability, changes in the way energy is produced e.g. coal-fired plants against renewable energy sources are limited so far.

In a same vein, Hoffmann (2007), drawing on interviews conducted with five companies of the German electricity market, suggests, that the EU ETS in principle spurs innovation per se and companies are taking emission trading into account when it comes to decision making. However, companies are shy of undertaking real changes such as large-scale investment decisions with long amortization times due to the lack of stringency and uncertainty.

Based on cross-country data for seven EU countries, Schmidt et al. (2012) conduct a multivariate study founded on firms’ perceptions of environmental policies in the energy sector, and find, that none of the ETS phases significantly triggered non-emitting technology adoption, and only Renewable Energy Technologies demand-pull policies had that effect.

Thereby, a major suspicion is, that market-based policies do have an impact on technological change but policy stringency is of great importance

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[22] In the case of the CAA, air quality increased due to more environmentally friendly innovations

whether firms engage in low-carbon technological change the EU ETS or not[23]. This point was recognized by Porter and van der Linde (1995) to ensure that well-designed environmental regulations spur innovation. The lack of policy stringency is attributed primarily to the accumulation of EUAs due to external shocks and lax emission caps, but exacerbated by the introduction of KOs into the system. These circumstances would seem to compromise incentives to engage in the innovation of new-to-the-market CCMTs and, at the same time, to undermine the "induced innovation" hypothesis in the case of the EU ETS. However, while this suspicion has been repeatedly voiced, it has yet to be tested empirically using historical data.

In the following sections we therefore conduct this empirical exercise that allows us to make a twofold contribution to the literature. First, we show how stringency under EU ETS, expressed through the oversupply on the one hand and policy regime changes on the other, affects the innovative behavior of firms under the EU ETS and beyond. We thereby give a first percentage estimate of these two effects under the EU ETS. Second, we separate the impact of the oversupply and policy changes with respect to overall CCMTs and technologies for the reduction of GHG related to energy generation, transmission or distribution.

4. Data Sources and Variables

In order to account properly for the cross-national character of the EU ETS, we constructed a longitudinal data set covering the 27 member states of the EU plus the EFTA-state Norway between 2005 and 2012, thus taking the first two trading periods into account. Although the EU ETS is currently operating in 31 countries, at the time of this analysis a complete set of data was only available for those 28 countries. Croatia only joined the EU (and, hence, the EU ETS) in 2013 and so falls outside the time frame of our analysis. As for the other two EFTA-EEA states in the system, Lichtenstein and Iceland, a full set of all the variables could not be completed. However, the possible distortion created by leaving out these two small countries is likely to be relatively low given their

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[23] Given the fact that over 90% of CCMTs in our data set are originating from the energy sector, we mainly focused on literature related to this sector. However, it is worth mentioning, that several more studies, such as Kneller & Manderson (2012), Anderson et al. (2011), Fontini & Pavan (2014), Aghion et al. (2009), Martin et al (2012), and Calel and Dechezleprêtre (2016), were analyzing how market-based regulations, and especially the EU ETS affect technological change.

minor role as polluters in the EU ETS. Our final data sample comprises 217 observation pairs.[24] Data for this study have been taken from Eurostat, with the exception the variables related to the EU ETS (allocated allowances and verified emissions), which source was the Community Independent Transaction Log (CITL).

4.1 The dependent variables: Patent Counts for CCMT

To measure the innovative activity of firms covered by the policy we use patent counts of CCMTs as a proxy. Advantages and disadvantages of using patents as an output measure of the creative process have been carefully considered (Griliches 1990; Wagner & Wakeman 2016). The typical drawback of patent data is that they only capture part of the outcome of innovative activities, since not all technological improvements are patented, voluntarily or otherwise, while innovations might also be of an organizational nature. Bearing these shortcomings in mind, patent data are a valid and frequently used measure for the innovative activity of firms, sectors, or countries.

The patent counts used in this study were created originally by the EPO and subsequently aggregated to the country-level by Eurostat. Every newly filed patent at the EPO is classified according to the International Patent Classification (IPC), recently enriched by the introduction of the new patent class, Y02, for patents providing CCMTs.[25] The Y02 class is built from several subclasses, including Y02-B, -C, -E, and -T. Given the focus of this paper, only patents from subclass Y02E are used here, as the other subclasses correspond to technologies that lie outside the scope of the EU ETS[26]. Thereby, subclass Y02E includes technologies for the reduction of GHG emission, related to energy generation, transmission or distribution.

An initial inspection of data for the Y02 patents shows several peculiarities. The most striking is the heterogeneity in the number of patent counts per country. In our sample, twelve countries[27] account for most CCMT patent applications at the EPO and together account for over 60% of overall

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[24] Bulgaria and Romania joined the EU and, thus, the EU ETS, in 2007, and so data for these two countries are only available thereafter. Norway joined the EU ETS in 2008 and so again only a reduced set of data is available.

[25] Veefkind et al. (2012) and EPO (2013) provide more details for the contents of the Y02 class and its subclasses.

[26] Even though technologies of the Y02C class find appliance in the energy sector, they do so as well in other sectors and a clear separation would not be given.

[27] Austria, Belgium, Germany, Denmark, Spain, Finland, France, UK, Italy, The Netherlands, Norway, and Sweden.

patent applications. Additionally, we identify a strong outlier –Germany-, which accounts for more than three times the mean number of applications than the country ranked second, France. This is discussed and taken into account when modeling the relationship between innovative behavior and oversupply of certificates. A further interesting observation emerges on presenting only patents of the Y02E class. Over 90% of patents classified as Y02 fall into the subclass Y02E. In other words, most of the patents in our sample have been developed for the energy sector. This is very interesting since this sector is one of the largest polluters in the trading system and, hence, deserves a special attention when it comes to measuring the impact of policy stringency.

4.2 *The explanatory variables*

Explanatory variables have to fulfill different tasks in regression equations. In our case, we identify the following groups of explanatory variables so as to address different features of the number of patent applications per country. As we are interested in measuring the impact of the policy on patent counts, our "core" variables are the oversupply of allowances and the binary variable controlling for policy changes between the two trading phases. Furthermore, and in order to specify correctly policy stringency on patenting behavior and so as not to mistakenly attribute the effects of other influences to these variables, we use a broad set of controls. We employ lagged business enterprise and government R&D spending,[28,29] measured as percentage of GDP, and the number of workers with tertiary education, given that these variables are known to be highly influential in determining innovation output (Griliches 1984).

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[28] We also checked for overall patenting trends in our regressions, using overall patent counts divided by the population of a country for a given year. However, this trend variable is highly correlated with business enterprise R&D and, hence, caused severe multicollinearity problems in our regressions. When introduced separately, the variable showed high statistical significance and the expected positive impact on CCMTs. Nevertheless, we choose to use business enterprise R&D expenditure first because its well-known impact on patenting activity and, second because the use of either of the two variables does not change conclusions of our estimates (Regressions using patenting trend available upon demand).

[29] With respect to the chosen lag structure in our estimations, we used in most cases the first-order lag, (t-1). The main reason behind the use of this structure is stemming from new evidence by Wang & Hagedoorn (2014) which found direct evidence that a lagged structure should be used to model patents, whereby, the first lag, (t-1), showed to be the only statistical significant lag among all model specifications in their work. Additionally, the authors confirm the existence of the U-shaped relationship between patents and R&D expenditures meaning that higher order lags, e.g. (t-5), impact patenting activity again. These higher-order lags, however, are not feasible in our study given the short time horizon in our panel due to policy characteristics.

An additional set of covariates is introduced to capture the economic performance of countries during the period of observation and respective industry size. We employ these variables because it is reasonable to think that costs of compliance are rising with higher economic performance corresponding to the sectors covered by the policy. Therefore, a relation between economic performance and CCMTs, as a mean to reduce the cost of compliance may exist. These variables are industry indices for the three main sectors -Mining and Quarrying (NACE B), Manufacturing (NACE C), and Energy (NACE D) –covered by the policy and annual GDP growth rates. All variables measuring countries' and sectors' economic performance are lagged one year since it is reasonable to think that last year's economic outcomes influence patent rates this year, given the time span an innovation needs in order to be eligible for patenting. As shown earlier, energy related patents make up the vast majority of CCMT patents. Following Edenhofer et al. (2012) and to incorporate that fact we introduce the share of energy from renewable sources into the equations as this is an obvious indication of "green" technological change.

Since we are particularly interested in the role of EUA oversupply on patenting behavior and major policy changes, we examine these variable in greater detail. Given that the main principle underpinning the EU ETS is that of 'cap and trade' and the capping is achieved through the allocation of emission allowances, the overall number of allowances on the market determines the degree of stringency of the policy. We would expect a scarcity of allowances to put pressure on firms to cut their emissions and to reduce the costs of compliance by employing cost efficient means. But the reality is somewhat different. External shocks and lax emission caps have resulted in a sizable oversupply during the second and third trading periods, having a negative effect on firms' decisions to engage in low-carbon technological change (measured here in patent counts for CCMTs). In this study, the oversupply stock is defined as the annual accumulated number of excess EUAs of all member states in the market; that is, the difference between the total numbers of allowances allocated in the market and total emissions in each respective year accumulated over years.[30] Additionally, and to correctly take policy features into account such as the cancelation of allowances from the first phase in the second phase, the stock of oversupply is calculated separately for the two trading phases. We opted for

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[30] Using this aggregation of the oversupply implies that there is no country variation among our data sample for this variable

this form of calculation as firms do not only access their own oversupply but also that of the market as whole, given the presence of a common market place. When having a look at the descriptive statistics of the oversupply variable in Table 1, it becomes apparent that during the observed time frame the vast majority of countries under the EU ETS were able to build up sizable oversupply.

As the different trading phases are marked by major policy changes, a regression equation analyzing these policy shifts needs to take this into account. For this reason, we created a dummy variable equal to 1 for years belonging to the second trading period and equal to zero for those belonging to the first period. This allows us to identify whether patenting behavior changed during the shift from phase one to two. Considering that the second trading phase tightened emission caps and reduced the share of certificates allocated free of charge this policy shift equals an increase in policy stringency and should positively affect patenting behavior. Furthermore, a detailed overview of the variables used, including their descriptive statistics, units of measurement and labels can be found in Table 1 as well.

Table 1: Variable Overview

Variables	Description	N	mean	sd	min	max
Y02	Number of Patent application at the EPO for the Y02 category	217	75.47	167.7	0	1,056
Y02E	Number of Patent application at the EPO for the Y02E category	217	72.25	161.3	0	1,017
GDP_growth	Percentage change of GDP on previous year	217	1.524	4.223	-17.70	11
renew	Share of renewable energy in gross final energy consumption	217	15.11	13.27	0.300	64.80
nace_b	Volume index of production for the mining and quarrying sector; data adjusted by working days	217	108.3	21.03	61.91	224.8
nace_c	Volume index of production for the manufacturing sector; data adjusted by working days	217	103.4	10.06	65.54	130.0
nace_d	Volume index of production for the energy sector; data adjusted by working days	217	98.91	7.515	75.87	119.1
BERD	Business enterprise R&D expenditure as percentage of GDP	217	0.915	0.690	0.0600	2.680
GORD	Governmental R&D expenditure as percentage of GDP	217	0.194	0.0887	0.0100	0.410
GDPvolume	Gross Domestic Product at current prices, million euros	217	471,488	688,090	5,142	2.758e+06
eua_ovs	Yearly accumulated oversupply of EUA in the market in Mgt.	217	2,043	2,356	-1,088	7,023
empl	Total Employees with tertiary education (levels 5-8) from age 25-64 in thousands	217	2,073	2,771	20	10,889
dummy_ets	Dummy for the shift from phase one to phase two of the EU ETS	217	0.686	0.465	0	1
Number of country		28	28	28	28	28

5. Methodology

In order to measure empirically the impact of the excess supply of EUAs, the following reduced form equations are estimated, employing a count data approach:

$$Patents_{i,t} = \alpha + \beta_1 L.eua_{ovs_{t-1}} + \beta_2 dummy\_ets_{i_{,t}} + \beta_3 empl_{i,t} + \beta_4 L.BERD_{i,t-1} + \beta_5 L.GORD_{i,t-1} + \beta_6 L.nace_{b_{i,t-1}} + \beta_7 L.nace_{c_{i,t-1}} + \beta_8 L.nace_{d_{i,t-1}} + \beta_9 L.GDP_{growth_{i,t-1}} + \beta_{10} L.renew_{i,t-1} + \mu_{i,t} + \varepsilon_{i,t} \tag{1}$$

where the dependent variable *Patents* is a count of patent applications registered at the EPO for different CCMT categories. To avoid stating very similar equations repeatedly, *Patents* is a placeholder for the Y02 and Y02E patent classes. *a* is the constant in the model. The core variables in our estimations are the lagged *eua_ovs* which represents the annual accumulated oversupply of EUAs in the market and the *dummy_ets* which reflects policy changes during the transition from Phase I to Phase II with values equal to zero for years belonging to the first trading period, and values equal to 1 for those belonging to the second trading period; *empl* is the total number of workers employed in the tertiary sector with educations levels 5-8 and age between 25 – 64 in the country; *L.BERD* and *L.GORD* are the lagged R&D expenditure by Business Enterprises and by Governments, respectively, measured as a percentage of GDP. The covariates L.*nace_b*, -*_c*, and –*_d* are lagged economic industry indices for the main sectors covered by the EU ETS: Mining and Quarrying, Manufacturing, and Energy. The variable L.*GDP_growth* is the lagged percentage change in GDP on the previous year. *renew* represents the percentage share of renewable energies in the gross final energy consumption. $\mu_{i,t}$ is the between-entity error and $\varepsilon_{i,t}$ is the within-entity error term of the random effect specification. The subscripts *i* and *t* define the cross-section and the time dimension of our data.

Count data models, more specifically Poisson and negative binomial regressions abound in the literature (Hausman et al. 1984; Cincera 1997; Cameron and Trivedi 2005; Johnstone et al. 2010), and are suitable for estimating the number of patent counts given their distribution characteristics. We use negative binomial random effects estimates on the grounds that an approach that supposes a Poisson distribution is too restrictive for our data as outlined in Figure A1 in the appendix demonstrates. Indeed, one of the requirements to use of a Poisson model is equi-dispersion; that is, equality of mean and variance:

$$E[Y] = V[Y] = \mu$$

However, the patent counts used here do not satisfy these criteria (see Table 1 for mean and variance relationship). This problem can be overcome using a negative binomial approach, whereby the mean still equals μ but the variance is allowed to increase by parameter $\alpha > 0$, allowing for unobserved heterogeneity across the sample. Hence, the first two moments of the negative binomial distribution are given by:

$$E[y|\mu, \alpha] = \mu$$

$$V[y|\mu, \alpha] = \mu(1 + \alpha\mu)$$

Recall that the variance now exceeds the mean, thereby addressing the problem of over-dispersion of the data and allowing unobserved heterogeneity to alter the mean-variance relationship. Moreover, we use random effects due to short panel properties and the corresponding incidental parameter problem (Cameron & Trivedi 2013, Hilbe 2011, Greene 2007).[31] Furthermore, we use the exposure variable *GDPvol*, because the number of patent applications at the EPO varies significantly from country to country, giving the impression that country size, measured in this study as GDP in volumes, matters[32]. In order to obtain robust standard errors for our coefficient estimates bootstrapping with 1000 replications is employed. A more detailed discussion regarding the robustness of our estimates and resulting bias, can be found in the appendix along with bias-corrected confidence intervals (Table A3 and A4). We use maximum likelihood as estimation method.

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[31] However, note that main estimation results using fixed effects are presented in Table A2 in the Appendix, since the Hausman test for random and fixed effects could not be estimated properly for all model specifications. The table shows that results using fixed effects do not significantly vary or alter the main outcomes presented in the text.

[32] Additionally, and for the case of Germany, an alternative way to take country heteroscedasticity into account is by using a country dummy for Germany. This has been done in an alternative estimation. However, the obtained coefficients do not vary for the remaining variables and the dummy itself is highly statistically insignificant. Results upon request.

6. Estimation Results

In line with the above described methodology, we performed the two main estimations for the Y02 class and its respective subclass, Y02E (Table 2). An initial inspection of the fit of the regressions for the main CCMT class and subclass leads to a number of observations. First, the overall model fit, given by the χ^2 statistic of the Wald test, can be provided for every equation since it rejects the H_0 of joint statistical insignificance. A likelihood-ratio test is used to check if the panel structure is justified or whether a pooled estimator with constant over-dispersion should be used. In each case, we reject the H_0 of constant over-dispersion; hence, the panel structure chosen for our model is valid. Third, we performed a multicollinearity test. This shows that all variance inflation factors are well below five suggesting that there are no problems of multicollinearity in our regressions (Table A1). The overall sample included 217 observations; however, due to the use of lagged variables the sample size was reduced by 28 observations for the regressions. Focusing on the different estimates of the Y02 and Y02E subclass, the variables known to have an impact on innovation are statistically significant for estimations (1) and (2); hence, for the main class, Y02, and the subclass, Y02E, they positively influence the patenting of CCMTs, as expected. More specifically, tertiary employment (workers with a good academic background) has a positive impact on the number of patent applications at a high significance level of 1%. Likewise, business enterprise R&D expenditure (*L.BERD*) has an even higher positive impact, being statistically significant at the 1% level for estimations (1) and (2). However, it is not the case of government R&D expenditure –the coefficient for *L.GORD* being statistically insignificant in both regressions. This suggests that the main driver of green technological change is private, rather than governmental, financing.

When focusing on the covariates measuring overall economic performance (L.GDP_growth) and the sector-specific performance (L.nace_b,c,d) interesting observations can be made. It seems that patenting activity in the Y02 and Y02E categories is not affected by an expansion of a country's economy of the previous year. This result suggests that broad indicator for countries' economic performance is not suitable to account for "green" innovation in our sample, neither for the overall patent category nor for patents related to the energy sector.

Table 2: Estimation Results for the Random Effects Negative Binomial - Main Equations

	RE regression for Y02	RE regression for Y02E
	(1)	(2)
L.eua_ovs	-4.23e-05***	-4.35e-05***
	(1.49e-05)	(1.43e-05)
1.dummy_ets	0.303***	0.298***
	(0.0509)	(0.0579)
empl	8.12e-05***	8.44e-05***
	(2.74e-05)	(3.28e-05)
L.BERD	0.897***	0.919***
	(0.186)	(0.179)
L.GORD	-0.820	-0.935
	(0.882)	(0.887)
L.nace_b	-0.000579	-0.000893
	(0.00231)	(0.00232)
L.nace_c	-0.00588	-0.00609
	(0.00374)	(0.00366)
L.nace_d	0.0152***	0.0157***
	(0.00506)	(0.00543)
L.GDP_growth	0.000990	0.000799
	(0.0105)	(0.0105)
L.renew	0.00199	0.00142
	(0.00627)	(0.00658)
Constant	-11.06***	-11.05***
	(1.230)	(1.130)
Observations	189	189
Number of Panels	28	28
F	143.7	132.1
Panel vs Pooled	261.2	260.1
Log-Likelihood	-594.6	-588.8

Bootstrap Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$
Note: A brief discussion of the use of bootstrap technique along with bias corrected confidence intervals can be found in the appendix (table A3 & A4)

However, when looking at the sector-specific economic performance the picture changes. While no statistical significant relationship between higher activity levels in the mining and quarrying (nace_b) and the manufacturing sector (nace_c) and patent activity can be found. On the other hand, the coefficient measuring the impact of performance of the energy sector shows high statistical significance and a positive relation with respect to “green” patenting activities. Having in mind, that the energy sector accounts for the lion’s share of CO2 emissions under the trading system, that more than 90% of CCMTs in our sample are patents related to energy production and distribution, the above result is hardly surprising. This suggests that, when it comes to Y02E patents, the policy has a positive effect on patenting in the respective sector. The use of the share of energy from renewable sources in the different specifications gives the expected positive coefficient across all regressions; however, the coefficient is statistically insignificant across the board, indicating that it does not affect green patenting in our sample.

The main purpose of the empirical exercise is to verify if the impact of the certificate oversupply is robust even when applying a broad set of controls and if policy changes related to higher stringency affect CCMT patenting. If we inspect the estimates corresponding to oversupply (*eua_ovs*), this would appear to be the case. The outcomes show high significance levels (at the 1% level) across the two main regressions. The sign associated with every equation is, as expected, negative, indicating that an increase in market oversupply reduces the overall number of “green” patents. Following the same intuition, the dummy variable marking the shifts between the two trading phases, similar to the oversupply, shows a high statistical significance at 1%, however, a positive impact on CCMT patents. This implies, that the shift from phase I to phase II can be considered as a positive stimulus towards more environmental-friendly technological change as the second phase increased the stringency of the EU ETS. These are the overt conclusions to be drawn from the statistical analysis; however, the implications of these results are complex.

Our results show that “green” technology change is closely related to the EU ETS as a whole, when measured in terms of patent applications registered at the EPO. Yet, the current situation of the EU ETS, characterized by an excess supply of allowances, cannot be considered to be conducive to technology change; on the contrary, it would appear to be discouraging it to some extent. Based on our regression results, firms under the EU ETS and as well firms not covered by the policy can be seen to be taking the oversupply of emission allowances into account when deciding what “green” innovative activity needs to be undertaken.[33] This means that the oversupply of allowances in the market, and the consequently low price for certificates, is causing the policy to lose much of its potential for fostering the technological change needed to achieve the EU's ambitious climate goals. This point gets even more clearer when considering the effects of policy changes expressed through the use of the dummy variable since higher stringency would lead to higher "green" patenting activity and, finally, to an increased environmental-friendly production.

In order to quantify these impacts, Figures 1 and 2 graphically display the impact for different oversupplies and the shift from Phase I to Phase II on the Y02 and Y02E category, respectively, in order to obtain a more comprehensive idea of the different effects taken place under the EU ETS. Thereby, we predict the average number of CCMTs under different scenarios for the overall oversupply[34] in the market due to our estimation results shown in table 2 and between the two trading phases. All other covariates in our regressions are allowed to vary as they do in our sample (Stata Corp LP (2013). For both figures, we can observe, first, that there is a clear negative relationship between the oversupply and the associated number of patent applications and, second, that the predicted number of patent applications varies considerably between the two phases as expressed through the upwards shift of the red curve compared to the blue curve.

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[33] As our regression results suggest, the oversupply has strong negative impact on overall patenting rates in the field of CCMTs. Recall that we use patent data not only for firms subject to the policy, but as well for firms outside. That is all CCMT patents.

[34] We decided to employ a range from -1000 MgT until 7000 Mgt since these two values mark the extreme values of accumulated oversupply in our data sample.

Figure 1: Estimated Number of Y02 patents for given levels of certificate oversupply and Phase I and II

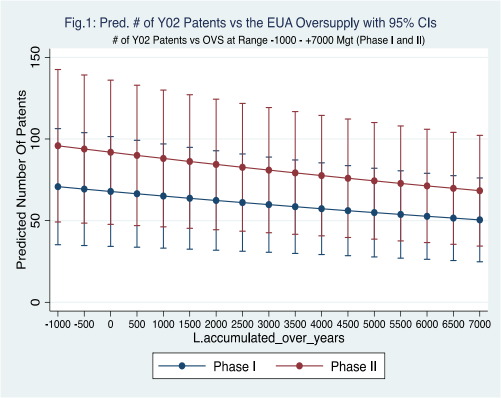
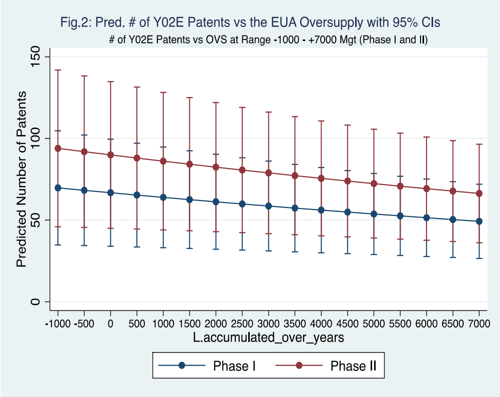


Figure 2: Estimated Number of Y02E patents for given levels of certificate oversupply and Phase I and II



Source (Fig. 1,2): Own Calculations based on estimation results shown in table 2

In addition to the graphical illustrations of the effects of the oversupply and the transition from phase I to II, table 3 presents numerical examples for those effects. As we see, the shift one trading phase to the other is associated to an increase of around 35% for the Y02 and the Y02E category, respectively, when evaluated at the mean of the accumulated oversupply. In the same line, we are interested to see what would be the expected number of patent applications if the oversupply would be reduced. As an example for this considerations, we calculated the expected increase of patent applications for the Y02 and Y02E category in the case of an oversupply reduction from its mean to a balanced supply, hence, an oversupply that equals zero. For this numerical example the resulting increase for both patent categories and phases are around 9% showing the strong negative impact of the oversupply on patenting behavior.

Table 3: Estimated Changes in Patent Counts due to Oversupply Reduction and Transition from Phase I to II

Oversupply Reduction (From Mean Oversupply to Balanced Supply)

	Y02 Patents		Y02E Patents	
	Phase I	Phase II	Phase I	Phase II
Mean Oversupply (2000 MgT)	62.37	84. 44	61.23	82.45
Balanced Supply (0 Mgt)	67.9	91.9	66.8	90
% Change Mean Oversupply to Balanced Supply:	**8.9%**	**8.8%**	**9.1%**	**9.16%**

Transition Phase I to II given the Mean Oversupply

	Phase I	Phase II	Mean % Change Phase I to Phase II
Y02 Patents			
Mean Oversupply (2000 MgT)	62.37	84. 44	**35.38%**
Y02E Patents			
Mean Oversupply (2000 MgT)	61.23	82.45	**34.64%**

Source: Based on estimations Table 2 and own calculations

At this point it is important to remember, that the Y02E category makes up for over 90% of overall CCMT patents. For this reason, the above described example vary only slightly between overall patent counts and patent counts for the Y02E category.

This situation is exacerbated by the other modes of compliance available to firms in the system, namely, KOs. These additional certificates of negligible price undermine even further the incentives to innovate by reducing the cost of compliance for firms.

Our findings show that the EU ETS, as a market-based regulation, has an impact on firms' levels of innovative activity (in terms of number of patents for CCMTs); however, so do policy failures. As we have shown, EU policy has been unable to generate a sufficiently high price as a result of oversupply. In addition, this can be seen as verification of the PH and of the circumstances under which environmental policies foster “green” innovation. The firms affected by the system are not responding to the policy as expected, owing to the negative impact of EUA oversupply on patent applications at the EPO on the one hand. On the other, policy changes related to greater stringency positively affect “green” patenting. Thus, in line with Porter & van der Linde’s (1995) claim, the stringency of the policy plays a vital role in determining whether an environmental policy will spur technological change. Here, we can assume that a shortage of EUA allowances in the market might serve to encourage innovation (Figures 2 and 3), a conclusion that indirectly validates the PH that well-designed market based regulations spur innovation.

7. Conclusion

In this study we have used patent count data for overall CCMTs and CCMTs related to energy production and distribution to evaluate the relationship between the sizable oversupply of EUAs and a policy shift marked by the transition from Phase I to Phase II under the EU ETS, on the one hand, and on “green” patenting, on the other. According to our results, the expected negative impact of this oversupply on technological change seems to be confirmed. Thus, firms take their emissions into account when determining their innovative activity. In the same vein, they do so with respect to policy changes related to greater stringency which generated a sizeable increase in patenting activity when controlled for other economic factors. However, firms also take policy failures, in this case the oversupply of certificates, into account. The latter is clearly apparent in the strong negative impact of the excess supply of EUAs on the number of CCMT patent applications. Therefore, two contrary but not mutually exclusive effects were taking place under the trading system.

From a policy perspective, several actions might be implemented to counter the negative impact of the oversupply. Although the EC introduced the “back-loading” of new allowances in the third trading period, a rigorous cancelling of allowances would help put the policy back on the right track and ensure firms rethink production in a more environmentally friendly way. A second approach, undertaken by the EC, is the introduction of a market stability reserve. In principle, this reserve should guarantee that a certain threshold of excess EUAs, 833 million allowances, is not passed. If so, the market stability reserve deducts the excess amount from future auction volumes (European Commission 2014b). Even though this approach sounds promising, its introduction is postponed until 2021, the start of the fourth trading period.

In addition, given that the market for EUAs adheres to the fundamentals of supply and demand in fixing prices, it is prone to external shocks such as the 2008 economic crisis that seriously hampered the systems credibility as a driver of low-carbon technologies. In order for the market to be less vulnerable to shocks, a price floor could be installed guaranteeing a minimum price for EUAs and, thus, providing the policy with both greater stringency and stability. Such a price floor would have to be sufficiently high to spur innovation, but low enough to avoid a crowding-out of production and a loss of competiveness in the EU. These measures would likely be opposed by the industrial sector, but they would put the policy back on track. Furthermore, and given the positive impact of an increase in policy stringency expressed by the shift from phase I to phase II, policymakers are urged to revise existing and future emission caps even against political resistance in order to firmly set the EU on a low-carbon pathway since this transition in our data sample is related to a considerable increase in “green” technological change.

From a scholarly perspective, our results suggest that market-based regulations have an impact on firms’ innovative behavior and when they are well-designed such regulations can spur innovation, as firms take the actual price of emissions on the hand, resulting from the supply of certificates, and higher stringency on the other into account.

All in all, the results presented in this work are robust for a broad set of controls and show the expected relationship. While we were able to show that the oversupply has serious impacts on the overall patenting behavior in the field of CCMTs in our data sample, future research should focus on the comparison of market-based regulations, as the EU ETS, and a suitable counterfactual in order to measure what would have been if there would not have been such a high excess of allowances and to validate our results. The main limitation of the study is the use of country-level data which we employed in our analysis and which allowed us to identify the overall impact of an excess supply of certificates on “green” patenting; however, future research should seek to use firm-level data. More specifically, the matching of single firms by patents and their respective shortage/oversupply of allowances could be used to cross-validate our findings. Likewise, a more detailed differentiation of sectors in the trading system is desirable.

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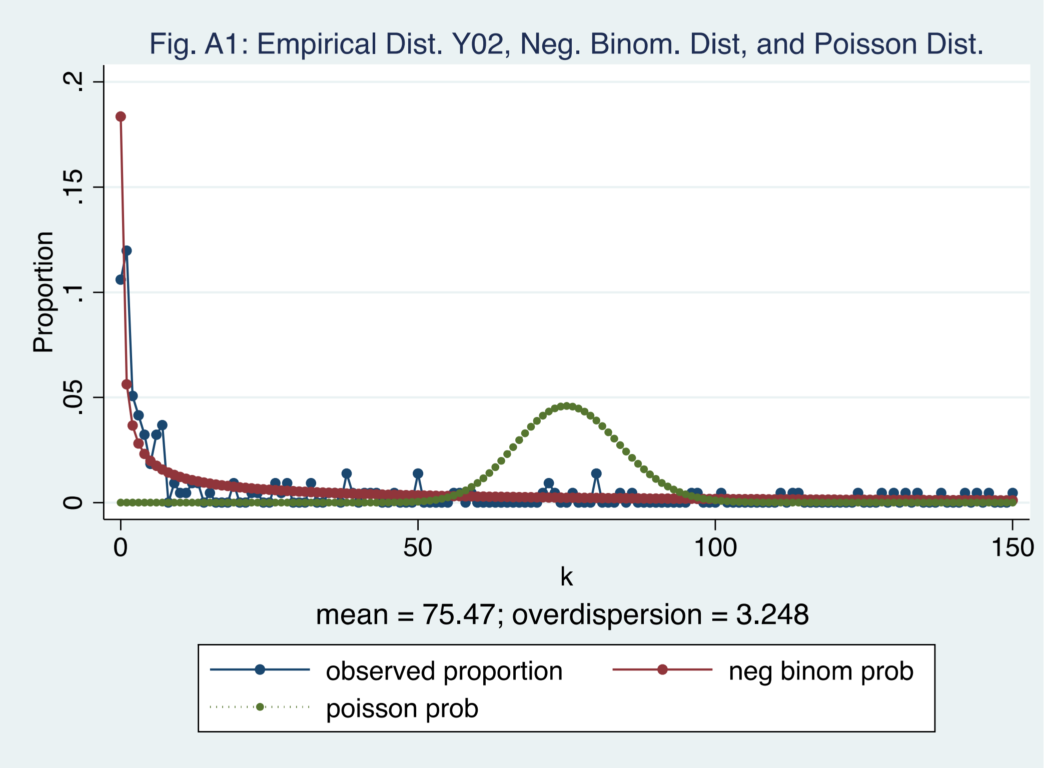
APPENDIX

Figure A1: Empirical Distribution of Y02 patent counts, Negative Binomial Distribution, and Poisson Distribution



Source: Own Calculation

Table A1:
Multicollinearity

Variable:	VIF
L.eua_ovs	1.13
empl	1.39
L.BERD	1.46
L.GORD	1.35
L.GDP_growth	1.44
L.nace_b	1.51
L.nace_c	1.39
L.nace_d	1.27
L.renew	1.46
dummy_ets	1.30
Mean VIF	1.37

Table A2: Estimation Results for the Fixed Effects Negative Binomial

	FE regression for Y02	FE regression for Y02E
	(1)	(2)
L.eua_ovs	-4.72e-05***	-5.00e-05***
	(1.46e-05)	(1.44e-05)
1.dummy_ets	0.254***	0.231***
	(0.0718)	(0.0662)
empl	0.000130	0.000143
	(0.000170)	(0.000148)
L.BERD	0.443	0.458
	(0.365)	(0.353)
L.GORD	-1.049	-1.244
	(1.770)	(1.890)
L.nace_b	-0.000855	-0.000981
	(0.00256)	(0.00252)
L.nace_c	-0.00383	-0.00382
	(0.00497)	(0.00449)
L.nace_d	0.0143**	0.0148**
	(0.00606)	(0.00595)
L.GDP_growth	-0.00415	-0.00519
	(0.0108)	(0.0103)
L.renew	0.0165	0.0205
	(0.0205)	(0.0189)
Constant	-10.68***	-10.75***
	-2.152	-1.847
Observations	189	189
Number of country_id	28	28
Log-likelihood	-444.2	-439.3
F	85.60	76.03

Bootstrap Standard errors in parentheses

*** p<0.01, ** p<0.05

Table A3: Bootstrap Statistics for Y02 Main Regressions

Y02 Estimation

Variables	Observed Coef.	Bias	Bootstrap Std. Err.	Bias Corrected 95% CI	
L.eua_ovs	-0.00004231	1.21e-07	0.00001489	-0.0000651	-1.14e-06
1.dummy_ets	0.30285061	-0.0872592	0.0509891	0.3011571	0.3669948
empl	0.00008119	-0.0000187	0.00002739	0.0000554	0.000174
L.BERD	0.8967919	-0.0029875	0.18639573	0.5580202	1.290858
L.GORD	-0.81988383	0.8897865	0.88158716	-2.364736	-0.4961863
L.nace_b	-0.00057921	-0.0007537	0.00231908	-0.0055886	0.0035368
L.nace_c	-0.00587567	-0.000895	0.00374239	-0.0112374	0.0045524
L.nace_d	0.01520467	0.0005891	0.0050665	0.0042161	0.0243689
L.GDP_growth	0.00099031	0.0015025	0.01052987	-0.0238923	0.019417
L.renew	0.00198707	-0.0034796	0.00627198	-0.0035301	0.0334494
_cons	-11.060052	0.8044522	1.2302487	-14.42964	-9.851769

Table A4: Bootstrap Statistics for Y02E Main Regressions

Y02E Estimation

Y02E	Observed Coef.	Bias	Bootstrap Std. Err.	Bias Corrected 95% CI	
L.eua_ovs	-0.0000435	-7.61e-07	0.00001431	-0.0000645	-5.57e-06
1.dummy_ets	0.29753154	-0.0900356	0.05798752	0.2864695	0.4454681
empl	0.00008443	-0.0000218	0.00003283	0.000063	0.0001832
L.BERD	0.91935097	0.0043223	0.17971756	0.5384822	1.237758
L.GORD	-0.93454461	0.8202854	0.8872565	-2.563458	-0.5251221
L.nace_b	-0.00089334	-0.0007591	0.002327	-0.005792	0.0038918
L.nace_c	-0.00609018	-0.0010591	0.00366387	-0.0118202	0.003368
L.nace_d	0.01567101	0.0005973	0.00543457	0.0029716	0.0249605

L.GDP_growth	0.00079945	0.0016735	0.01050609	-0.0218497	0.0201261
L.renew	0.00141611	-0.0033343	0.00658138	-0.0039071	0.034089
_cons	-11.053.978	0.7319055	1.1306838	-13.5108	-9.984615

Remarks on table A3 and A4:

Since we are using bootstrapping in order to obtain robust estimates for our standard errors we want to take closer look at the bootstrap results for our two main regressions in Table 2. The main idea of bootstrapping is to estimate the standard error by drawing repeatedly bootstrap samples from the original data using sampling with replacement and fit the model repeatedly. In our case, we use 1000 bootstrap replications of our data sample. As the model is fit over and over again an bias estimate of the observed statistic and the bootstrap estimates can be constructed (Stata Corp. 2015) along with bias-corrected confidence intervals (CI). As can be seen in tables A3 and A4 some coefficient estimates of our main equation are exhibiting a slight bias, we are interested if these estimates are still within a CI which takes the bias into account. For this reason, the bias-corrected CI intervals along with their estimated bias are presented here. As can be seen in tables A3 and A4, even though bias is present for some estimates, all statistical significance coefficients of our main estimation in table 2 are well inside the bias-corrected CI allowing us to make us of them for further inference and predictions.

Chapter 4: Climate Change Mitigation and the Role of Technologic Change: Impact on selected headline targets of Europe's 2020 climate and energy package

1. Introduction

The first, legally binding global climate deal, adopted by 197 countries in Paris (COP 21) in December 2015, is soon to come into effect, placing all participants under considerable pressure to honor their pledges. Yet, as highlighted by the 2014 report published by the Intergovernmental Panel on Climate Change (IPCC) on climate change mitigation (Edenhofer et al. 2014), the headline target of the Paris Agreement – limiting global warming to a maximum of two degrees in the long run – will be difficult to achieve unless there are major improvements in energy efficiency. Moreover, the report stresses the key role to be played by policies that can cut the demand for energy by fostering investment in energy efficiency projects. In short, technology change as it impacts energy production and energy end use is critical for maintaining global warming below two degrees.

Prior to the Paris Agreement, the European Union, a pioneer in combating climate change, launched a set of policies as part of its 2020 climate and energy package aimed at meeting its 20/20/20 headline targets for smart, sustainable and inclusive growth. As such, technology change explicitly underpins its policy framework; yet, and to the best our knowledge, there has been no ex-post assessment of the role technology change might play in achieving these goals. Recent studies in the literature concern themselves, primarily, with evaluating the ways in which public environmental policies stimulate "green" technology change, but they do not intend to determine how effective these technologies are in achieving established policy goals and whether their impact varies across sectors. Here, therefore, we seek to measure, first, how successful new-to-the-market climate change mitigation technologies (CCMT) are in helping EU member states (MS) reach these goals and, second, whether there are differences between sectors subject to EU-wide polices. To do so, we seek to relate CCMT patent counts to two specific headline targets, namely, achieving 20% of gross final energy consumption from renewables and achieving a 20% increase in energy efficiency. Thanks to the richness of our data, we are able to determine the impact of different CCMT classes on overall target achievement and on sector-specific achievement rates. Our results provide the first ex-post evaluation of the effectiveness of these technologies for combating climate change. Furthermore, our impact assessment conducted by sector points to significant differences in the way in which these technologies contribute to policy goals across sectors. As such, our study both broadens our understanding of the impact CCMTs can have and serves to make policy recommendations aimed at ultimately reaching the ambitious climate goals set by the EU and placing it firmly on the pathway to low carbon.

The rest of the study is organized as follows. In section two, we present a brief overview of the 2020 climate and energy package and its respective policies,[35] and in order to provide a clear picture of where the EU currently stands we report the descriptive statistics in relation to headline targets and CCMT measures. This section is followed by a brief literature review in which we examine the most relevant findings. Next, the data for the empirical exercise are introduced along with their descriptive statistics. Section five introduces the reader to the empirical strategy applied in section six where we present the regression results and discuss the special role played by CCMTs. Finally, in section seven, we conclude the study with a number of policy recommendations and we discuss the limitations and potential lines of future research

2. The EU "2020 climate and energy package" and its respective policies

In 2010, the European Commission (EC) established five headline targets, better known as the Europe 2020 Strategy, outlining where the EU should stand on key parameters by 2020 (European Commission 2010). In order to meet its energy and climate change goals, the EC put together the "2020 climate and energy package", comprising a set of binding legislation to ensure the following targets are met: (1) 20% reduction in greenhouse gas (GHG) emissions; (2) 20% of gross final energy consumption from renewables; and (3) 20% improvement in energy efficiency (European Commission 2016).

2.1. A 20% reduction in GHG emissions.

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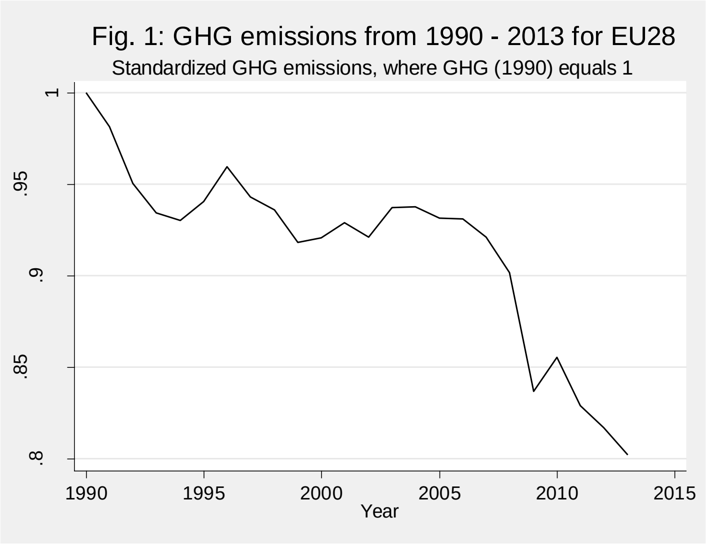
[35] Other types of action taken by the EU in order to meet the 20/20/20 goals include research and innovation programs such as the NER 300 and the Horizon 2020 programs. Both programs do not just tackle a single goal of the 2020 climate and energy package, but aim to benefit all three of them. While the NER 300 program focuses on the funding and diffusion of new-to-the-market low carbon technologies, such as carbon capture and storage technologies (CCS) and renewable energy technologies, the Horizon 2020 program pursues, among other goals, the financing of research and innovation in the areas of resource efficiency and the sustainable supply of raw materials. Special attention, therefore, is paid to waste/water management and resource efficient economies (European Commission 2015b).

The key tool for achieving this target is the EU Emissions Trading System (EU ETS), an EU-wide regulation, covering around 45% of Europe's GHG emissions and applied to energy-intensive industries and, since 2012, to commercial airlines. The ETS is complemented by an additional policy targeting the reduction of emissions – the "Effort Sharing Decision", which applies to sectors not covered by the EU ETS, including transport, housing, waste, and agriculture. However, in this instance, the policy is not applied homogeneously across MS; thus, because of their differing growth prospects, the richest MS need to reduce their emissions by 20% whereas the least wealthy MS are permitted to increase their emissions in the respective sectors by 20%. As such, and in contrast with the EU ETS, the "Effort Sharing Decision" relies on national emission reduction plans.

The EU seems to have made considerable progress towards this first goal, to the extent that Figure 1 suggests that achieving the target is simply a matter of time. According to Eurostat (2014a), by 2012 the EU had achieved an 18% cut in GHG emissions from 1990 levels. Yet, this progress cannot be attributed solely to the efforts of the EU and its policies; it also reflects the impact of major external factors, in particular the effects of the 2008/09 economic crisis. As stressed by Bel & Joseph (2015), the main driver of emission abatement for sectors under the EU ETS was the economic recession and only a relatively small proportion of the abatement could actually be attributed to policy.

Figure 1: EU-28 GHG emissions, 1990-2013



Note: Total GHG emissions including international aviation and excluding LULUCF
Source: Own calculations

Given that the 2020 climate and energy package's first goal is within sight, we do not examine in any further depth the effects of CCMTs and GHG abatement here. Moreover, this particular target does not concern our empirical analysis because targets 2 and 3 (see above) very much condition this first goal. Thus, an increase in the share of renewable energy sources in gross inland consumption by fuel type goes hand in hand with a reduction in GHG emissions. Likewise, it is reasonable to assume that a reduction in final energy consumption by means of efficiency enhancements also leads to a reduction in GHG emissions.[36]

2.2. A 20% renewable energy share.

This target is included in the "Renewable Energy Directive" and, in common with GHG reduction policies, national renewable targets vary across MS, depending on their initial position and overall potential (European Commission 2009). For example, Sweden is required to achieve a target of 49%, while Malta has been set a goal of just 10% (National Renewable Energy Action Plan Sweden 2010; National Renewable Energy Action Plan Malta 2010). The directive aims to foster cooperation among MS by promoting three mechanisms: statistical transfers of renewable energy, joint renewable energy projects, and joint renewable energy support schemes. Additionally, the directive promotes the use of sustainable biofuels in order to meet a 10% renewable energy target in the transport sector (European Commission (a) 2015).

Considerable progress has also been made with respect to the sources of renewable energy. Gross inland energy consumption[37] by fuel increased from 8.9 to 13.3% over the period 2005 through to 2012 (Figures 2 and 3), representing a growth of 49% over the whole period. At the same time, all the other shares of gross inland energy consumption (GIEC) by fuel type dropped, the largest fall being recorded by petroleum products (~ 3% reduction). These substitution effects are worth stressing since the burning of fossil fuels, for such

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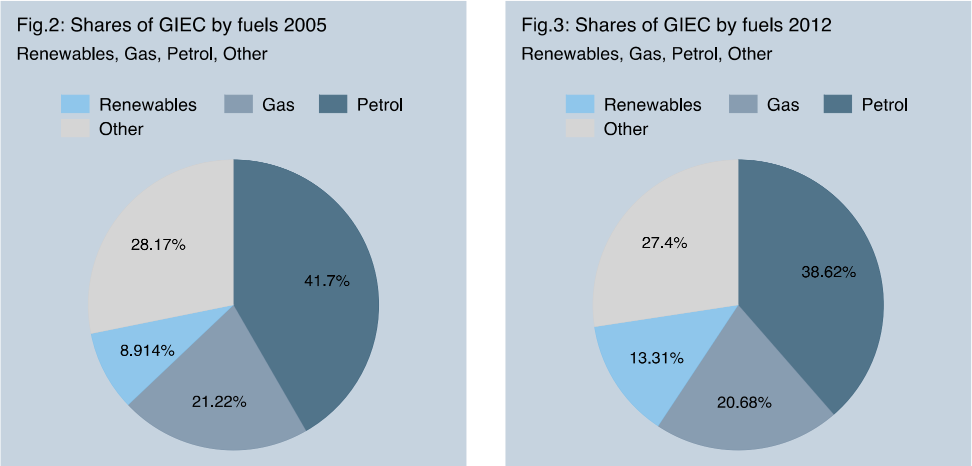
[36] We are aware of critical views of this hypothesis, e.g., Herring (2006). However, the kind of energy savings/efficiency increases as outlined in the Energy Efficiency Directive 2012/27/EC do not favor a reduction in the implicit energy price; hence, "rebound" and "takeback" effects are not expected.

[37] Here, we use gross inland energy consumption as opposed to gross final energy consumption. While we are aware that the goals set out in the "2020 climate & energy package" employ the latter indicator, gross inland energy consumption (see definition in Appendix) provides good approximation.

activities as the production of electricity and transport, is one of the main drivers of climate change (EPA 2016; NASA 2016)[38].

However, the positive overall trend conceals huge differences between countries: Sweden, Bulgaria, and Estonia have already met their 2020 renewable energy targets, while many, including Malta, Netherlands, the UK, and Luxembourg are some distance from reaching their respective goals (Eurostat 2014). Hence, much has to be achieved to ensure that all MS hit the 2020 target of a 20% share of renewables in gross final energy consumption.

Figures 2 & 3: Shares of gross inland energy consumption by fuel type (GIEC), 2005 and 2012



Source: Eurostat & own calculations

2.3.A 20% improvement in energy efficiency.

To achieve the 2020 climate & energy package's third goal, the EC issued Directive 2012/27/EU, that is, the Energy Efficiency Directive (European Commission 2012). The directive is built on three pillars that seek to ensure the 20% increase in efficiency is met. The first comprises the National Energy Efficiency Action Plans (NEEAP) and annual reports. The NEEAPs include the estimated energy consumption, planned energy efficiency measures, and the individual goals of each MS and have to be revised and resubmitted on a three-year basis. The annual progress reports serve to verify whether targets have been reached.

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[38] The category "other" in the figures includes solid fuels, nuclear heat, and waste.

The second pillar comprises the so-called national building renovation strategies, whereby each MS indicates how they intend to stimulate investments through the targeting of renovation in the commercial and residential building sectors. Additionally, the EU states are obliged to renovate at least 3% of their government building stock.[39] The third pillar comprises the energy efficiency obligation schemes. These schemes target energy distributors or retail energy sales companies with the aim of achieving a 1.5% energy saving in annual sales to final consumers by means of the implementation of energy efficiency measures.[40]

In assessing the achievement of this energy efficiency target, two points need to be borne in mind: first, the indicators used to measure the energy efficiency of the MS and, second, the base year selected. As regards the former, several indicators can be used to describe energy efficiency[41]; however, the EC ruled that national targets should be expressed as either primary energy consumption or final energy consumption[42] (European Commission 2013). In the case of the second point, the EC established 2007 as the baseline projection for energy consumption. Accordingly, the EC estimated that 1,853 Mtoe (million tons of oil equivalent) of primary energy will be consumed in 2020 (European Commission 2012). A 20% reduction would correspond, therefore, to a primary energy consumption of 1,482 Mtoe or a final energy consumption of 1,086 Mtoe, respectively (The Coalition for Energy Savings 2013).

In our data sample one single sector is responsible for nearly one third of final energy consumption in the EU, namely, the transport (31.8%)[43]. The trends recorded in sector-specific final energy consumption are shown in Fig. 5, highlighting a number of interesting observations. First, the evolution in final energy consumption differs in the transport sector compared to the remaining

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[39] EU countries, as an alternative to renovating 3% of government-owned or -used buildings, have the option of implementing behavioral changes or undertaking major renovation work (i.e., increasing energy performance above minimum requirements). To be considered valid, the work must achieve the same degree of energy savings.

[40] MS can also opt for alternative policy measures that boost increase energy efficiency, including energy/ carbon taxes, training and education and financial incentives for the deployment of energy efficiency technologies.

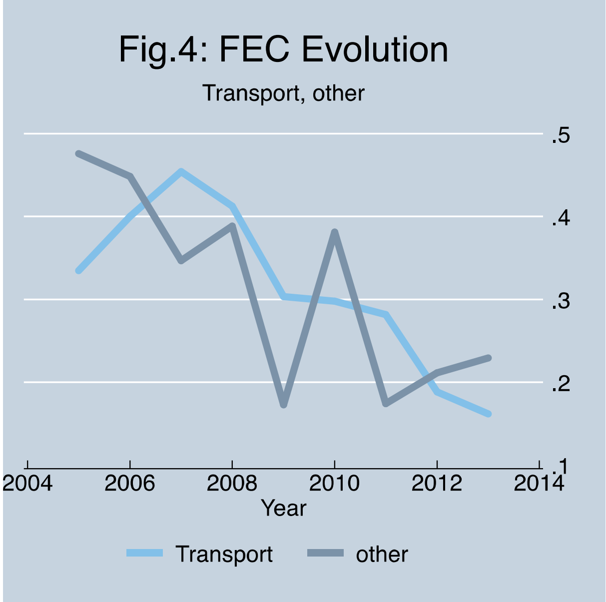
[41] They include Primary Energy Consumption, Final Energy Consumption, Final Energy Savings, and Energy Intensity.

[42] A definition of both can be found in the Appendix.

[43] We focus on overall and transport specific FEC, as we are particularly interested in the way in which CCMTs impact energy efficiency overall and sector specific. However, data for sector-specific CCMTs were only available for the transport sectors, which limited our analysis accordingly.

sectors. While there appears to be a downward trend in consumption in the transport sector (following a minor increase between 2005 and 2007), consumption fluctuates in the remaining sector. Hence, consumption in the transport sector does not seem to be as volatile against economic performance as are the other sectors since "other's"[44] final energy consumption experienced a sharp increase in the recovering of the economic crisis 2008/2009 while the transport sector steadily reduced its consumption.

Figure 4: Final Energy Consumption (FEC) by Sector



Note: Fig. 5 uses standardized FEC consumption for the sector "other" and the transport sector for comparability reasons. Source: Eurostat & Own Calculations.

Finally, during the observation period energy efficiency increased overall; thus, final total energy consumption fell by 7.1% between 2005 and 2012. However, the reduction in final energy use is not spread evenly across sectors; in the case at hand, final energy consumption in the transport sector reduced by "only" 4.75% suggesting that other sectors where responsible for the major decrease in consumption.

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[44] The sectors included in this category are Industry, Agriculture/Forestry, Services, Residential, and other (non-specified), with Industry accounting for the largest share.

3. Related literature

In recent years, much has been written about the relationship between the impact of environmental policies and technology change. However, when it comes to meeting the goals of these policies, much less has been written about the specific impact of new-to-the-market technologies.

Many studies draw on the “induced innovation” hypothesis that was first formulated by Hicks (1932) and which was later reformulated in terms of environmental policies by Porter & van der Linde (1995) and renamed the Porter Hypothesis, which states that well-designed environmental policies can foster the deployment of environmental-friendly technology change. One study that examines this relationship in depth is Popp (2003). Popp exploits a policy regime change from a classical command-and-control regime to a market-based approach to study the effects on patenting activity, and the effectiveness of new patents, following the introduction of the Clean Air Act (CAA) in 1990. Thus, while patenting activity – measured in patent counts – fell after the introduction of the CAA, the focus taken by R&D activity also shifted. Before the transition to market-based regulation, companies affected by the policy concentrated their R&D efforts on reducing the costs of compliance with the regulation; after 1990, their R&D was more concerned with improving the efficiency of technology aimed at reducing emissions. Although the absolute number of patents fell in 1990, the market-based approach increased the efficiency of new patents aimed at guaranteeing a more environment-friendly production.

Using patent data to determine the role environmental policies play in relation to the development of technological innovations in renewable energy sources (RES), Johnstone et al. (2009) show that different kinds of policy instrument favor the innovation of different RES. Overall, the paper finds that public policy plays a key role in fostering new-to-the-market technologies. In the case of the more costly RES (e.g. solar energy), targeted policy instruments, such as feed-in-tariffs, have a significant effect on such technologies; whereas, broad-based policies, such as emission trading, foster technology change that is competitive with conventional energy sources.

Further evidence that environmental policies are an important factor when it comes to “green” technology change can be found in Haščič et al. (2010). This paper identifies a link between policies combating climate change and the generation and diffusion of CCMTs. However, evidence is presented that innovation not only depends on public policy but also on a country’s innovative capacity. Thus, there is a classic mismatch between the needs of developing countries with respect to specific CCMTs and the development of these technologies given their lack of innovative capacity. In contrast, developed countries lack the incentives to develop these technologies. As the authors suggest, cooperation between these two parties would overcome this mismatch.

Focusing on the European flagship policy for climate change mitigation, the EU ETS, Calel and Dechezleprêtre (2016) match EU ETS firms with firms not affected by the policy and apply a difference-in-differences estimation in an attempt at separating the impact of the policy on the development of low-carbon technologies from other external factors. The authors measure technological change in terms of the number of patent applications registered at the European Patent Office (EPO). In this way, they are able to untangle the surge in CCMT patenting that coincided with the launch of the EU ETS in 2005. According to their estimates, the policy was responsible for almost a 1% increase in CCMTs, when compared to the counterfactual scenario. Furthermore, their firm-level estimates highlight that the EU ETS has, on the one hand, a limited impact on overall low-carbon patenting, while, on the other, the policy has a strong and targeted effect on a small set of firms under the regime.

Probably the most related work to ours stems from Soltmann et al. (2014). Using industry-level panel data, the paper aims to explain the link between green innovation and performance, measured as value added. In that way, the authors showed that the relation between green innovations and performance is U-shaped meaning that for most industries the associated effect is negative up to a certain turning point. Nevertheless, this study does not answer our research questions: to what extend green technologies can contribute to reach climate policy goals.

Several more studies have sought to explain the link between environmental regulation and technology change (Jaffe & Palmer (1997), Jaffe et al. (2002), Popp (2006), Anderson et al. (2011), Fontini and Pavan (2014)); however, they all take a different focus on the ways in which environmental policies impact on technological change. Yet, to the best of our knowledge, no study to date has analyzed the effectiveness of these technologies with respect to the different goals established by environmental policy. With this objective in mind, we seek to provide an initial measure of how CCMTs, in general, contribute to achieving climate and energy targets and, more specifically, how the different branches of these technologies impact on sectoral policy measures. Thus, we focus on the

European 20/20/20 goals and their respective measures, as outlined above, and the impact of selected CCMTs. In this respect, our study is, we believe, the first to undertake the impact assessment of different CCMTs and policy headline targets. However, before undertaking the empirical analysis, the data used in this study are presented along with their summary statistics.

4. Data

Because the European 20/20/20 goals and their respective policies are of a cross-country character, we constructed a longitudinal data set covering all 28 MS of the EU from 2005 until 2012 in order to capture this.[45] Our final sample comprises a total of 224 observations. The data for this study have been taken from three sources: PATSTAT, Eurostat, and the World Bank Database. All data for the different CCMT patent classes have been extracted from PATSTAT, the official patent register of the EPO, and then aggregated to country-levels in order to match the aggregation levels of the other covariates. From this latter database, commodity prices for oil, coal, and natural gas have been taken. All other data, including the final energy consumption and the share of renewable energy in gross inland energy consumption, were taken from Eurostat.

4.1 The evolution of CCMTs between 2005 and 2012 and their link to Europe's 20/20/20 goals

As we are particularly interested in the impact of CCMTs on two of the "2020 climate and energy package" goals (20% increase in renewable energy sources and a 20% reduction in FEC), we begin by examining the evolution of these specific technologies. As a proxy for green technologies, we use patent applications for CCMTs filed at the EPO. Much attention has been dedicated to examining the advantages and drawbacks associated with this proxy (Griliches 1990). The main drawback of patent data is that they only capture part of the outcome of an innovative activity, since not all technological improvements are patented, voluntarily or otherwise, while innovations might also be of an organizational nature.

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[45] Note that we not only evaluate the 20/20/20 goals per se but consider the way in which the CCMTs can play a role in achieving these goals. That is why we focus both on the timeframes for the different policies which are making up the climate and energy package as well as on the longer time horizon.

Bearing these shortcomings in mind, patent data are nevertheless a valid and frequently used measure for the innovative activity of firms, sectors, or countries. These patents are grouped under the patent class Y02 and its respective sub-classes Y02B, -C, -E, and -T[46], which were recently created to keep track of green technologies (Veefkind et al. 2012). Given the focus of this paper, only patents belonging to the super-class Y02 and to the sub-classes Y02E, and -T are used further in this study. Thus, we associate the goal of a 20% increase in renewable energy sources to patents in the Y02E category, that is, patents associated with achieving a reduction in GHG emissions during energy generation, transmission and distribution (EPO 2015a). The goal of a 20% increase in energy efficiency is linked to the Y02 super-class for total FEC, and to the Y02T sub-class (CCMTs related to transportation (EPO 2015b)) for the FEC of the transport sector.

If we examine the evolution of the different CCMTs in our database, we see (Fig. 6) that every single category has experienced considerable growth over the observation period,[47] with Y02-E and –T category patents being responsible for the greatest increases in absolute numbers. With this in mind, and comparing these findings with those related to an increase in the share of renewables and with both overall and sector-specific energy efficiency/drop in FEC, there would appear to be a causal relationship between them.

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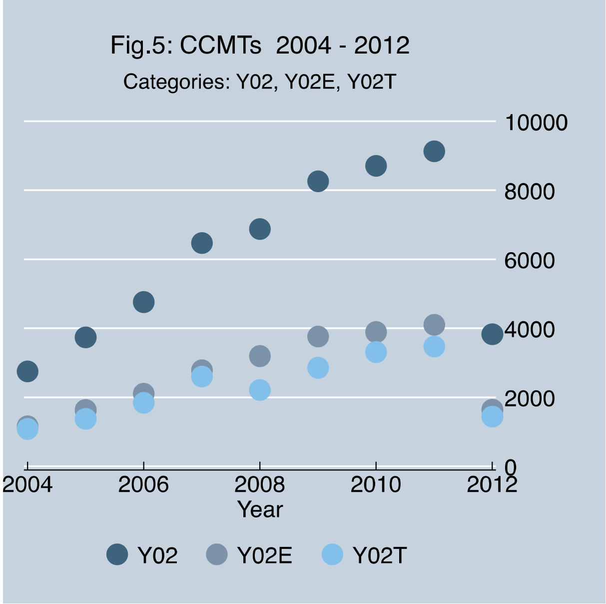
[46] A detailed description of the different patent classes can be found in Table A1 in the Appendix together with example technologies for each category.

[47] Note that the fall in number of CCMTs in the years 2012 is not due to a reduction in innovative activity among the MS; rather, it reflects the time lag between patent applications and patent approvals. We discuss this when considering CCMTs as a regressor in the estimations.

Fig. 5: CCMTs over the period 2004 to 2012 (EU Aggregates)



Source: PATSTAT & Own Calculations

Since companies can not only access new technologies of a given year but as well technologies from previous years, we use patent stocks instead of patent flows. Additionally, and following Munari and Oriani (2011) this patent stock depreciates on a yearly basis in order to address the fact, that knowledge becomes outdated over time. Formally, the patent stock for year *t* and country *i* was created using the following equation:

$$Patent\ Stock_{i,t} = (1-\delta)Patent\ Stock_{i,t-1} + Patents_{i,t} \qquad \text{(I)}$$

, where Patent Stock equals the accumulated patent counts for the Y02, Y02E, and Y02T patents, respectively, and Patents are the newly developed technologies of a given year. δ is the depreciation rate. We decided to employ a depreciation rate of 15% per year guided by the studies of Jaffe (1986), Cockburn and Griliches (1988), Hall and Oriani (2006)[48]. In order to identify correctly the impact of CCMTs on the different policy measures a broad set of control variables was employed. Thus, we clearly distinguish between the goals

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[48] Nevertheless, we additionally performed all regressions using depreciation rates between 10% and 30% (in steps of 5), whereby the outcomes are relatively stable over the whole range which is in line with Jaffe (1986)

of a 20% increase in the share of renewables and a 20% increase in energy efficiency.

4.2 Variables concerning the 20% increase in the share of renewable

As discussed, we use GIEC by fuel type as our dependent variable in the case of this specific target. Given that we are especially interested in the role of CCMTs related to energy production/consumption, our key variable is patent counts in the Y02E category (that is, patents related to energy generation, transmission and distribution). We opted to use this patent class only as these technologies are closely related to our dependent variables in this section.

Additionally, and so as not to falsely attribute any effects to these technologies, we exploit several more covariates. We employ GDP growth rates in our model to determine whether a country's economic performance in a given year influences GIEC. A second set of covariates includes commodity prices, given that a change in the relative price of a specific commodity due to a price change in another might possibly increase/decrease its use for energy production. Therefore, the prices of oil and coal are included as regressors in our model[49]. To account properly for the demand side of energy consumption, we embed the number of manufacturing enterprises in our model.

Finally, we use the number of electricity[50] firms in our regressions. If a country has a high number of such firms, it is more likely to have a higher share of renewables in its production mix than countries with just a few but dominant companies. This rational is motivated by the fact that renewable energy facilities, compared to conventional power plants, are more dependent on location and country endowments and, in general, produce less energy than, for example, coal-fired plants. Thus, in order to meet demand, more of these plants/companies are needed. Therefore, we would expect a negative impact on GIEC from fossil fuels and a positive impact on GIEC from renewables in our regressions.

4.3 Variables concerning a 20% increase in energy efficiency

In the case of a 20% increase in energy efficiency, the dependent variable is final energy consumption (FEC) (see discussion above). First, we wish to determine the overall effect of CCMTs on total FEC. Our first estimate uses total FEC per country in a given year as the endogenous variable. Second, we are interested

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[49] Due to multicollinearity issues, we do not include natural gas prices in our regressions.

[50] Enterprises included in the NACE D category (Electricity, gas, steam, and air condition supply).

in how sector-specific CCMTs contribute to an increase in energy efficiency in the transport sector. Thus, the sector-specific specification uses the FEC of the transport sector. In common with our first goal, our core variable here are the CCMTs related to the different sectors. These comprise patent counts for the Y02 category for total FEC and Y02T counts for the FEC of the transport sector.

Additionally, we control for other factors that might influence FEC. Thus, we employ GDP growth rates in our specifications to capture any impact of economic performance on FEC. Furthermore, employment rates are included because of the close relationship identified with energy consumption (Tivari 2010). Moreover, and as above, the number of manufacturing enterprises is included as there may be a causal relationship with FEC. The energy intensity of an economy and of the transport sector also form part of the specification, since we expect a greater intensity to have, in general, a positive effect on overall FEC and on the consumption in the respective sector. Energy intensity in this study is calculated as the ratio between FEC (total and sectorial) and real GDP for a given year and country.

In the case of the sectorial equation, additional covariates are employed to control sector-specific trends. For the transport sector, we used the different modal splits for passenger and freight transport on both roads and rail, since a shift from one mode to the other may influence the FEC of the transport sector. Finally, we included a measure of the quantity and performance of road transport, namely, tons of goods transported per kilometer during the observation period. A detailed overview of all variables used in the empirical analysis can be found in Table 1.

Table 1: Summary Statistics and Description

VARIABLES	Description	N	mean	sd	min	max
GIEC_renew	GIEC by renewable energy sources; 1000 tons of oil equivalents (TOE)	224	5,321	6,537	0.500	32,252
GIEC_petrol	GIEC by total petroleum products; 1000 tons of oil equivalents (TOE)	224	22,555	30,275	869.5	121,893
GIEC_gas	GIEC by Gas; 1000 tons of oil equivalents (TOE)	224	15,292	22,807	0	85,473
GIEC_total	GIEC total; 1000 tons of oil equivalents (TOE)	224	62,954	84,462	870.4	351,704
FEC_total	Final energy consumption total; 1000 tons of oil equivalent (TOE)	224	41,006	53,913	381.5	223,424
FEC_trans	Final energy consumption Transport; 1000 tons of oil equivalent (TOE)	224	13,183	17,743	197.5	63,406
gdp_growth	Real GDP growth rate; Percentage change on previous year	224	1.604	4.331	-14.80	11.90
oil_brent	Crude oil, Brent, $/bbl, real 2010	224	81.95	15.41	62.07	104.1
coal	Coal, Australia, $/mt, real 2010	224	84.48	24.15	54.30	123.6
emp_rates	Employment rate (15 to 64 years); annual averages	224	64.25	6.000	50.80	77.90
num_manu	Number of Manufacturing enterprises	224	80,573	97,042	816	481,813
num_ele	Number of enterprises belonging to the NACE D category	224	1,526	2,852	3	18,554
modal_pass_road	Modal split of passenger transport; Passenger cars; percentage	224	81.42	5.317	64.20	92.30
modal_pass_train	Modal split of passenger transport; Trains; percentage	224	5.648	3.177	0	12.60
modal_freight_rail	Modal split of freight rail transport; percentage	224	19.19	15.99	0	70.20
tonnePerKilo	Transported Tons of Freight per Kilometer; Thousand Tons	216	66,435	81,963	896	343,447
enrInt_total	Energy Intensity total economy, FEC/real GDP (in millions)	224	0.134	0.0625	0.0586	0.438
enrInt_trans	Energy Intensity Transport Sector, FEC/real GDP (in millions	224	0.0426	0.0171	0.0198	0.125

Table 1: Summary Statistics and Description (continued)

Y02_dep15	Patent stock for the Y02 category (Depreciation Rate 15%); priority date	224	419.2	1,074	0	7,334
Y02E_dep15	Patent stock for the Y02E category (Depreciation Rate 15%); priority date	224	186.2	442.8	0	3,083
Y02T_dep15	Patent stock for the Y02T category (Depreciation Rate 15%); priority date	224	156.0	472.8	0	3,162
Number of groups		28	28	28	28	28

Note: In the case of "*tonnePerKilo*" no data could be obtained for Malta. Possible disturbances due to this missing data is discussed in the result section.

5. The econometric specification

As we wish to analyze the specific impact of CCMTs on two key targets of Europe's climate and energy package, two sets of estimations are performed for each goal. The first set of estimations concerns the goal of achieving a 20% increase in energy from renewable sources. We not only show how the CCMTs of the Y02E category impact the GIEC of renewable sources, but also how these technologies affect the shares of sources other than renewables and overall consumption. The following equation is estimated for the GIEC for each fuel type:

$$GIEC\ by\ fuel_{i,t} = \alpha + \beta_1 Y02E\_dep15_{i,t} + \beta_2 gdp\_growth_{i,t} + \beta_3 coal_{i,t} + \beta_4 oil\_brent_{i,t} + \beta_5 num\_manu_{i,t} + \beta_6 num\_elec_{i,t} + u_{i,t} \qquad \text{(II-V)},$$

where *GIEC by fuel* is a placeholder for GIEC by renewables, gas, petrol, and overall consumption (in order to avoid repeating the same equation). α is the model's constant. *Y02E_dep15* is the patent stock for the Y02E category applying a 15% depreciation rate. Thereby, the stock for the first year, 2005, are the depreciated patent counts of year 2004 plus the patent counts of year 2005. In this manner, we do not only make use of a stock but as well incorporate the fact that there might be a delay between the patenting of a technology and its actual use in the production process. *gdp_growth* is the real GDP growth rate, measuring a country's overall economic performance. The variables *coal* and *oil_brent* represent coal and oil prices in our regressions, respectively. The number of manufacturing and electricity enterprises is represented by the variables *num_manu* and *num_elec*. Finally, *u* is the error term of the econometric specification, capturing all non-observable characteristics of GIEC. The subscripts *i* and *t* determine the cross-section and the time dimension of the variables, respectively.

Our second set of estimations seeks to capture the overall and sector-specific impacts on FEC of CCMTs, that is, how increased energy efficiency can be achieved by employing "green" technologies. Thus, we are first interested in the effects of CCMTs on total FEC and, second, in specific CCMT effects on FEC in the transport. The two resulting estimation equations can be stated as follows:

$$FEC\_total_{i,t} = \alpha_i + \beta_1 Y02\_dep15_{i,t} + \beta_2 gdp\_growth_{i,t} + \beta_3 emp\_rates_{i,t} + \beta_4 num\_manu_{i,t} + \beta_5 enrInt\_total_{i,t} + u_{i,t} \tag{VI}$$

$$FEC\_trans_{i,t} = \alpha_i + \beta_1 Y02T\_dep15_{i,t} + \beta_2 gdp\_growth_{i,t} + \beta_3 emp\_rates_{i,t} + \beta_4 num\_manu_{i,t} + \beta_5 enrInt\_trans_{i,t} + \beta_6 modal\_freight\_rail_{i,t} + \beta_7 modal\_pass\_road_{i,t} + \beta_8 modal\_pass\_train_{i,t} + \beta_9 tonnePerKilo_{i,t} + u_{i,t} \tag{VII}$$

where *FEC_total* and - *trans* are the corresponding energy consumptions for total FEC and the transport sector. α is the constant of the specification in the two equations. The variables Y02*_dep15* and *Y02T_dep15*, are the patent stocks for the respective sector and in total following the same considerations as in equations II - V. As above, *gdp_growth* is the annual real GDP growth rate. *emp_rates* represent the annual mean employment rates in our sample. *num_manu* stands for the number of manufacturing enterprises per country and year. *enrInt_total*, and *-_trans* are the respective energy intensities of the studied sectors. With respect to the sectorial specification, additional covariates are included to capture sector-specific dependencies.

The FEC equation for the transport sector (Eq. VII) includes these additional variables: *modal_freight_rail, modal_pass_road, modal_pass_train,* and *tonnePerKilo*. The first three represent the modal shifts in freight and passenger transport[51]

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[51] We did not include the modal share of road transport with respect to freight transport because of strong multicollinearity issues.

and the last represents tonnes of goods transported per kilometer by freight transport.

We decided to employ a fixed effect estimator in order to capture non-observable, time-invariant country heterogeneity. This approach can be considered appropriate since country differences are pronounced in our sample given differences in population, demographics, and political systems, to identify just a few. By using a fixed effect estimation, we automatically take these factors into consideration. The results of the Hausman test, conducted to determine whether to use fixed or random effects, however, are not trustworthy in the case of our regressions. Nevertheless, in line the above reasoning, we favor the use of the fixed effect specification.[52] Due to the presence of heteroscedasticity and cross-section dependency in our sample, we employ Driscoll-Kraay standard errors in order to obtain robust estimates of our standard errors.

6. Results

In this section we present the results of the regressions described above. We first describe the results concerning a 20% increase in the share of renewables (Table 2) and, second, the results related to energy efficiency and CCMTs (Table 3).

6.1 A 20% increase in the share of renewables and the effect of CCMTs in the energy sector

As can be observed in Table 2, all estimations show overall statistical significance, since the F-statistic in each case (Eq. II-V) leads to the rejection of the H_0 that all coefficients are jointly equal to zero. Furthermore, the goodness-of-fit for equations I-IV, measured as the within R^2, shows high values for equations II-IV and a moderate level for equation V. Finally, the full set of EU countries is used in this empirical exercise resulting in 224 observations.

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[52] Our main results do not vary greatly when random effects are used. These results are available from the authors upon request.

Table 2: Fixed Effects Estimation Results for GIEC by fuel

	(II)	(III)	(IV)	(V)
VARIABLES	GIEC_total	GIEC_renew	GIEC_petrol	GIEC_gas
Y02E_dep15	-13.84***	4.768***	-5.904***	-3.308***
	(1.632)	(0.715)	(0.922)	(0.667)
gdp_growth	194.9***	-19.62**	66.17***	62.98**
	(17.06)	(6.654)	(8.778)	(24.36)
coal	39.46***	-8.991	21.31***	28.96***
	(6.760)	(5.465)	(2.796)	(3.460)
oil_brent	-58.59***	29.37**	-42.38***	-51.83***
	(14.60)	(8.593)	(2.875)	(5.486)
num_manu	0.207***	-0.0738***	0.189***	0.0661***
	(0.0276)	(0.0103)	(0.0204)	(0.00474)
num_ele	-0.443**	0.182***	-0.499***	0.0628
	(0.133)	(0.0507)	(0.107)	(0.0947)
Constant	50,717***	8,487***	10,765***	12,183***
	(3,087)	(590.5)	(1,526)	(631.9)
Observations	224	224	224	224
Number of groups	28	28	28	28
F-statistic	700.6	110.8	173.5	438.0
R^2(within)	0.546	0.638	0.717	0.239

Driscoll-Kraay standard errors in parentheses

*** $p<0.01$, ** $p<0.05$

All the variables used in our regressions show the expected behavior. Starting with the control variables employed to capture all effects other than those caused by CCMTs, we can see that total GIEC and GIEC by fuel type are sensitive to the overall economic performance of countries, measured as real GDP growth rates (gdp_growth). Their coefficients present high (Eq. II, IV) to moderate (Eq. III,V) statistical significance throughout all the estimations. However, the impact of GDP growth rates is not the same for all four estimations. While positive growth rates have a positive impact on total GIEC and on GIEC from petrol or gas sources, the impact on the share of renewables in GIEC falls with increasing GDP growth rates. This suggests that in order to meet the energy needs of a growing economy, energy producers rely more on conventional fuel sources than they do on renewable sources; thus, there is no sign of any decoupling of energy from different sources and economic growth measured in GDP growth rates. In the case of the impact of coal prices in our regressions for GIEC by fuel type, the resulting sign might initially be surprising, as it seems to point to a substitution effect among energy consumption by fuel type. Indeed, rising coal prices lead to a greater consumption of the other sources (namely, petrol and gas). The same impact is observed for total GIEC. This is hardly surprising if we consider that nearly 60% of total GIEC is made up from GIEC from petrol and gas sources.

However, the same does not hold for GIEC from renewable sources. Following our estimation result for this category (Eq. II), no statistically significant relationship between GIEC and renewable and coal prices can be found. As for crude oil prices (*oil_brent*), the sign and significance levels obtained are as expected. Thus, higher oil prices reduce the share of petrol and gas sources, as well as total GIEC, while GIEC from renewables is affected positively. If we recall, however, that the lion's share of GIEC is made up from petrol and gas sources, this result is expected. However, the close relationship between crude oil, on the one hand, and natural gas, on the other, should be borne in mind when seeking to understand the negative impact of rising oil prices on GIEC from gas sources (Asche et al. 2006).[53] Given that the manufacturing sector is one of the largest consumers of energy, the resulting positive sign and high significance of the coefficient representing the number of manufacturing enterprises (*num_manu*) in equations II, IV, and V are expected.

However, here again, this estimation result is not valid for the GIEC of renewables sources (Eq. III) as it appears that a larger manufacturing sector negatively influences the share of renewables in GIEC. In order to meet the energy needs of this sector, energy producers seem to rely more heavily on fossil fuels, in a similar relationship to that observed for the impact of GDP growth rates. As predicted in section four, a higher number of energy firms in a country positively impacts GIEC from renewable sources (Eq. III) and negatively impacts total GIEC and GIEC from petroleum sources (Eq. II & IV). However, no statistically significant result could be obtained for GIEC from gas sources, even though the obtained sign presents a negative impact of *num_elec* in equation V.

In the case of our variable of interest, the patent stock for the Y02E patent category (*Y02E_dep15*), all coefficients present high levels of statistical significance and their impact follows the underlying theory. For total and for sources other than renewables, the impact of the CCMTs of the energy sector

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[53] Given the close relationship between crude oil and natural gas prices and the resulting multicollinearity problem, we decided to employ crude oil prices only in our regressions.

is negative with respect to GIEC (Eq. I, IV, and V) while the impact on GIEC from renewables is positively influenced by these technologies (Eq. III).

Given that we are particularly interested in the impact of these technologies, Figures 6-9 describe their impacts on the different GIEC analyzed in this study for different levels of the Y02E patent stock. The range, which indicates the impact of Y02E-categorized technologies, extends from 0 to the mean Y02E patent stock plus two times its standard deviation (~1100). Bearing in mind that the average patent count stands at around 186, we are able to draw some conclusions with respect to the share of renewables in GIEC and the other fuel sources. As expected, and in line with the regression results presented in Table 2, GIEC is reduced by an increasing number of Y02E patents for total, petroleum, and gas sources (Figs. 6, 8, and 9) and increases for GIEC from renewable sources (Fig. 7).

Focusing specifically on the goal of achieving a 20% share of energy from renewables, we are interested in determining what would happen to GIEC from renewables if there were an X% increase in Y02E patents in our data sample. This relationship can be obtained in a straightforward manner as we employ a linear prediction. For example, a 10% increase of the Y02E patent stock from its mean would result, on average, in an increase of around 1.61% in GIEC from renewables. A rise in the number of patents from 186 to 205 would result in an increase in GIEC from renewables in our sample of between 5,320 TOE and 5,406 TOE, on average. Indeed, a scenario in which CCMTs are increased by 10% is not unusual. For example, and given our data sample, the average Y02E patent stock increased by 10% between 2009 (227 Y02 patents) and 2010 (249 Y02 patents).[54] This result underlines the important role that CCMTs can play to meet the goal of a 20% share of renewables in gross final energy consumption. Hence, policies fostering the innovation and deployment of these technologies can be of core relevance to reach this goal.

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[54] As discussed above, patent counts for the Y02 class and its subclasses experienced a fall after 2011. If we restrict our analysis to the 2005-2011time horizon, the impact of CCMTs increases slightly; however, our overall sample size decreases. Given this trade-off, we opted to use the full as opposed to the reduced sample. As such, our estimates are a conservative estimate of the impact of CCMTs, given that future increases in these technologies could have an even stronger impact on policy measures.

Fig. 6: Predicted Margins of Y02E stock on GIEC total

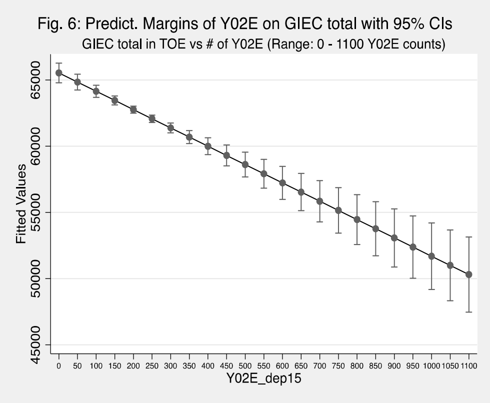


Fig. 7: Predicted Margins of Y02E stock on GIEC from renewables

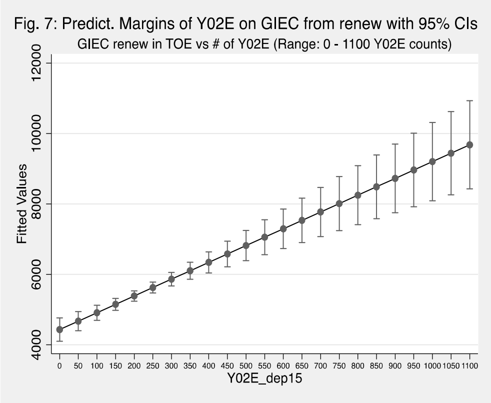


Fig. 8: Predicted Margins of Y02E stock on GIEC by petroleum

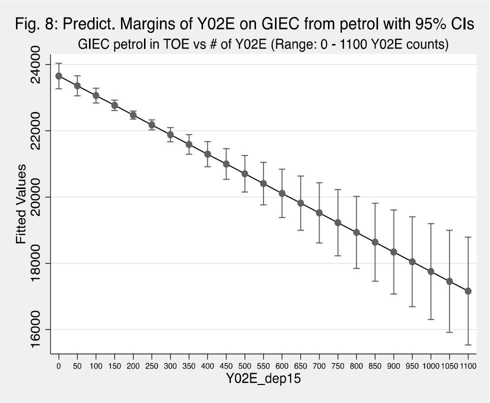
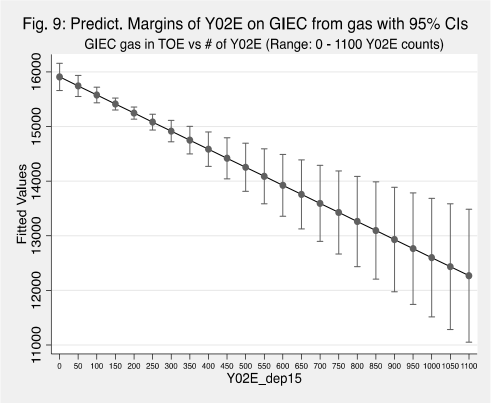


Fig. 9: Predicted Margins of Y02E stock on GIEC from gas



Note: Predicted margins are based on estimation results shown in Table 2

Finally, as can be seen in Table 2, it seems that all the covariates that have a positive effect on total GIEC and on GIEC from petroleum and from gas have a negative impact on GIEC from renewables, and vice versa. This peculiar observation may be important in designing future policies targeting GIEC from different fuel sources.

6.2 A 20% increase in energy efficiency and the effect of CCMTs

Table 3 presents the impact of CCMTs with respect to the target of a 20% increase in energy efficiency together with various covariates for total FEC and by end-use sector. In line with the previous results, the overall fit of equations (VI) and (VII) is given, as indicated by the corresponding F-statistic values. The proportion of variability of the dependent variables explained, as expressed by the R^2 statistic, extends from around 46% for FEC total to around 74% for FEC in the transport sector. It should be noted that for regression (VII) only 216 observations were available, as a full set of data for all the covariates could not be obtained for Malta. However, given the overall size of Malta, any potential disturbance created by not including these observations is expected to be minimal. As with the previous results, we first discuss the impacts of our control variables and then focus on the effects of CCMTs in our regressions.

The first variable that all three estimations in Table 3 have in common is *gdp_gowth,* representing real GDP growth rates and accounting for the overall economic performances of the countries in our sample and the link to FEC. Given that this variable presents a moderately positive statistical significance only in the case of total FEC (Eq. VI) and not for the sectorial equations (VI), it would appear that such shocks as the global economic recession did not influence FEC across the MS in the transport sector. This result is in line with Fig. 6, where total FEC showed a relationship with economic performance and FEC in the transport sector did not fluctuate during the years of economic recession or recovery but instead decreased continually. However, as one of the aims of the Energy Efficiency Directive is to decouple energy use from economic growth, no statistically significant relationship at all would be desirable.

As for employment rates, for total FEC and FEC in the transport sector, the expected positive link is present between these two variables, indicating that total FEC and FEC in the transport sector are sensitive to the overall employments rates of a given country and year. Total FEC and FEC for transport are, furthermore, influenced by the total number of manufacturing enterprises. The reasons for the positive and statistically significant impact on total FEC are the same as those outlined for Eq. II in Table 2, whereas the positive and significant sign in the case of the transport sector reflects the close link between the manufacturing and transport sectors with the latter supplying the former.

The last of the variables that the two equations (Eq. VI-VII) have in common is the respective levels of energy intensity (*enrInt_total,* and - *_trans*). In each case, the coefficient indicates a positive impact on the respective rates of FEC and is statistically significant at 1%, thus capturing the general trends in overall FEC and in consumption across sectors.

Table 3: Fixed Effects Estimation Results for FEC (total, transport)

	(VI)	(VII)
VARIABLES	FEC_total	FEC_trans
Y02_dep15	-2.739***	
	(0.743)	
Y02T_dep15		-1.052***
		(0.141)
gdp_growth	60.78**	-0.744
	(22.13)	(7.550)
emp_rates	204.6**	118.0***
	(68.66)	(13.94)
num_manu	0.165***	0.0468***
	(0.0126)	(0.00995)
enrInt_total	10,227***	
	(2,428)	
enrInt_trans		17,788***
		(3,627)
modal_freight_rail		50.31***
		(7.005)
modal_pass_road		108.5***
		(18.22)
modal_pass_train		-303.2***
		(71.78)
tonnePerKilo		0.0356***
		(0.00397)
Constant	14,255***	-8,749***
	(3,632)	(1,435)
Observations	224	216
Number of groups	28	27
F-Statistic	298.5	889.9
R^2(within)	0.456	0.742

Driscoll-Kraay Standard errors in parentheses
*** p<0.01, ** p<0.05

The variables that capture the specific characteristics of FEC in the transport sector (Eq. VII) all present high levels of significance. As expected, the modal splits for passenger transport (*modal_pass_road, - train*) highlight the fact that shifting from road- to rail-based modes in the case of passengers lowers FEC in the transport sector. However, this does not seem to hold for FEC in the rail freight transport. Here, an increasing share of rail freight transport increases FEC in the transport sector. Finally, we introduced *tonnePerKilo* as a load factor for road freight transport and, as expected, a positive impact is observed as this measure increases.

As our main objective is to quantify the impact of CCMTs on total FEC and on FEC in the transport sector, Figures 10 and 11 show these impacts graphically and comprehensively show how FEC is reduced by an increase in CCMTs.

Fig. 10: Predicted Margins of Y02 stock on total FEC

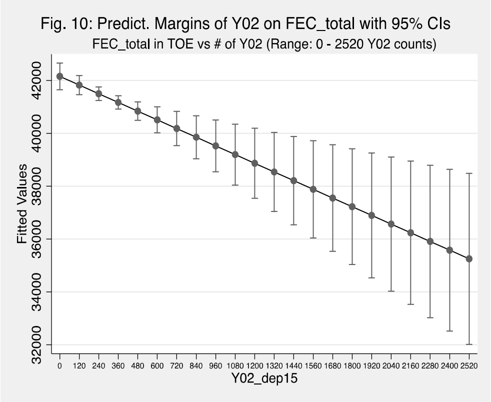
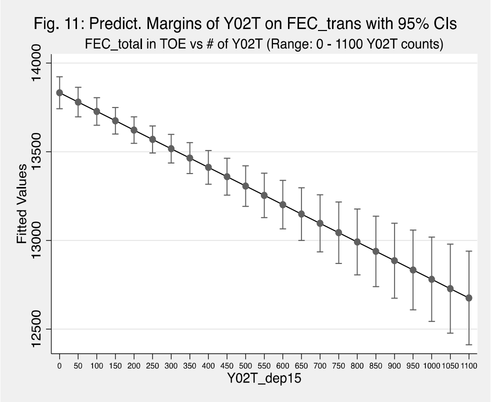


Fig. 11: Predicted Margins of Y02T stock on FEC in the transport sector



Note: Predicted margins are based on estimation results shown in Table 3

For the two different rates of FEC identified, we established different boundaries for the respective CCMT classes, since the average number of patents in each category varies from class to class. Thereby, the boundaries following the same criteria as the one used in Fig. 7-10. Thus, the boundaries extend from 0 to 2520 Y02 counts for total FEC and from 0 to 1100 Y02T counts for FEC in the transport sector. In line with the regression results, total FEC and FEC in the transport sector are reduced by an increasing number of CCMTs. However, this effect is not equal across the specifications. Once again, to illustrate this we increase the average number of CCMTs in our sample for each specification by 10% to determine the resulting percentage change. The results of this exercise are summarized in Table 4.

Table 4: Effect of a 10% increase of the respective CCMT stocks on FEC

Pred. aver. FEC total given a Y02 patent stock of 419	Pred. aver. FEC total given Y02 patent stock of 461	Percentage Change (%)
41006 TOE	40891 TOE	≈ 0.28%
Pred. aver. FEC_trans given 156 Y02T patent stock	Pred. aver. FEC_trans given 172 Y02T patent stock	
13668 TOE	13651 TOE	≈ 0.123%

Source: Own calculations

As can be seen in Table 4, the impact of CCMTs varies greatly between the transport sector and overall. Thereby, the effect on total FEC of CCMTs is more than twice as strong than that for the transport sector. One should bear in mind when interpreting the resulting impact of on FEC, that average yearly gross growth rates for the Y02 and Y02T group exceed 10% in most cases, hence, CCMTs help reach the goal of a 20% increase in energy efficiency. Nevertheless, and comparing the outcomes to the results obtained for GIEC for renewables, the impact of CCMTs on energy efficiency (measured here as final energy consumption) is to date limited; however, this could be the result of the non-appliance of these new-to-the-market technologies. Hence, extending the use of these technologies could be critical in determining whether the target of a 20% increase in energy efficiency is achieved or not.

7 Conclusion

We undertook this analysis with the aim of assessing the role that CCMTs play in meeting two of the three headline targets of the "energy and climate package". In so doing, we related the goal of obtaining 20% of gross final energy consumption from renewables with technologies corresponding to the energy sector (Y02E-patents) and the goal of achieving a 20% increase in energy efficiency with overall technological change (Y02-patents) and sector specific changes for the transport (Y02T-patents) sector. Our results show that CCMTs not only play an essential part in overall target achievement but that there exist significant differences in the impact of these technologies between sectors. We demonstrated that an increasing number of CCMTs related to energy production, transformation and distribution has a particularly marked impact on the share of energy obtained from renewable sources. Our example shows that a 10% increase of CCMTs in the Y02E category increases the GIEC from renewables by around 1.61%. Given that this increase of patents is actually present in our data sample the transition from year 2009 to 2010, for example, fostering the development of these technologies is crucial for achieving the target of a 20% share from renewables.

Furthermore, the results from the empirical exercise point to a strong, negative and statistically significant impact on fuels other than renewables from the development of Y02E patents. This finding suggests that by promoting these technologies the policy target is more likely to be reached and a considerable decrease in GIEC from fossil fuels, and the dependency on these sources, can be achieved.

In the case of the second target, achieving a 20% increase in energy efficiency, our results suggest that, first, the impact of CCMTs has been limited to date (especially compared to the impact of CCMTs on the first target), and second, the impact of CCMTs varies greatly across overall FEC and FEC in the transport sector. When we tested a scenario in which total CCMTs and sector-specific CCMTs were increased by 10%, the resulting decrease in total FEC was around 0.28%, compared to 0.123% for FEC in the transport. These results indicate that technology change is not affecting FEC evenly across sectors.

These results have several policy implications. First, technological change can play a key role in achieving the ambitious climate goals set by the EU, and hence policies such as the NER 300 program can make the difference as to whether these goals are met or not. Thus, expanding these policies and creating additional incentives for firms to innovate should place the EU firmly on the pathway to low carbon.

Furthermore, policies like the EU ETS seem to actively encourage the use of new technologies. This is very apparent if we compare the effects of CCMTs on the energy sector that is subject directly to the policy and the effects of CCMTs on firms that lie outside the policy, such as those in the transport sector. This leads us to our second policy recommendation, which is that policies need to foster the development of these technologies and ensure that these technologies are employed by end users across a range of sectors. In short, it is necessary to promote the application of new CCMTs. In the case at hand, this might result in an increased impact of these technologies in the transport sector, among others, where the impact to date has been limited.

As with most empirical studies, the factors that have placed some limitations on our evaluation are data issues. Although we have been able to separate the impact of CCMTs on FEC into overall and the transport sector, a more detailed breakdown would be desirable so that we might extend our analysis to include, for example, such sectors as manufacturing and waste. Finally, and in order to verify our results, follow-up studies would benefit from a higher data resolution, which would allow the effects to be detected more precisely.

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Appendix:

Definition of the different types of energy consumptions discussed in this study:

Primary Energy Consumption:

Primary energy consumption measures a country's total energy demand. It includes the consumption of the energy sector itself, losses during the transformation (for example, from oil or gas into electricity) and distribution of energy, and the final consumption by end users. It excludes energy carriers used for non-energy purposes (such as petroleum not used for combustion but for producing plastics) (Eurostat 2014 (b)).

Final Energy Consumption

Final energy consumption includes all the energy supplied to the final consumer for all energy uses. It is usually disaggregated into the final end-use sectors: industry, transport, households, services and agriculture (European Environmental Agency 2009).

Gross Final Energy Consumption

Energy commodities delivered for energy purposes to final consumers (industry, transport, households, services, agriculture, forestry and fisheries), including the consumption of electricity and heat by the energy branch for electricity and heat production and including losses of electricity and heat in distribution and transmission (European Environmental Agency 2015).

Gross Inland Energy Consumption

Gross Inland Energy Consumption (GIEC) is the quantity of energy, expressed in oil equivalents, consumed within the national territory of a country. It is calculated as follows: primary production + recovered products + total imports + variations of stocks - total exports - bunkers. It corresponds to the addition of final consumption, distribution losses, transformation losses and statistical differences (Eurostat 2016).

Table A1: The Y02 patent class and exemplary sub-classes Y02E/T (CPC classification)

Patent Class	**Definition**	**Examples**
Y02	Climate Change Mitigation Technologies	
Subclass Y02E		
Y02E	Reduction of GHG emissions related to energy generation, transmission or distribution	
Y02E10/00	Energy generation through renewable energy sources	Geothermal Energy / Hydro Energy / Energy from Sea / Photovoltaic (PV)Energy / Thermal-PV hybrids / Wind Energy
Y02E 20/00	Combustion technologies with mitigation potential	Combined combustion / Technologies for a more efficient combustion or heat usage
Y02E 40/00	Technologies for an efficient electrical power generation, transmission or distribution	Flexible AC transmission systems / Active power filtering / Reactive power compensation
Subclass Y02T		
Y02T	Climate Change Mitigation Technologies related to Transportation	
Y02T 10/00	Road transport of goods or passengers	Internal combustion engine [ICE] based vehicles / Exhaust after-treatment / Use of alternative fuels
Y02T 30/00	Transportation of goods or passengers via railways	Energy recovery technologies concerning the propulsion system in locomotives or motor railcars / Reducing air resistance by modifying contour
Y02T 50/00	Aeronautics or air transport	Drag reduction / Weight reduction / On board measures aiming to increase energy efficiency

Chapter 5: Conclusions

The presented discourse concerning major climate change public policies of the EU followed a clear plot where every new chapter answered arising questions of the previous. Thereby, the starting point tried to answer the questions to which extend the EU ETS was able to reduce emissions during its first two trading phases compared to the impact of the economic crisis 2008 – 2009. Respectively, in Chapter 2, using a dynamic panel data approach, we related a policy variable capturing the impact of the EU ETS and measures of the economic performance to GHG emissions under the trading system. The methodology, thereby, followed in big parts previous literature which makes use of a flow adjustment model in order to forecast CO_2 emissions. Furthermore, the policy measure is constructed as the difference of standardized GHG emissions from sectors under the EU ETS and outside the EU ETS.

We showed that the EU ETS only accounted for a minor portion of emission abatement during the years 2005 until 2012, namely, 33.78 – 40.76MgT out of the 294.5MgT. Therefore, 255MgT of emission abatement cannot be attributed to the impact of the policy but to other factors. As our results suggest one of the major impact on emissions was the economic crisis 2008-2009, instead. Thus, companies under the system reduced their emissions not due their own effort but due to the economic recession.

This fact, consequently, led to the built up of a sizeable oversupply of certificates in the market with far-reaching consequences. One of these consequences is a possible negative effect on firms' incentives to invest in low-carbon technologies which represent a key factor for decarbonizing Europe's economy.

Thus, Chapter 3 seeks to evaluate to which extend policy stringency under a market-based regulation affects the deployment of CCMTs with special focus on the energy sector since this particular sector solely is responsible for nearly one third of EU27's GHG emissions. Policy stringency is measured in two different ways here. On the one hand, we relate stringency to the excess supply of allowances in the market. On the other, we are focusing on the transition between trading phases which are marked by major policy changes related to greater stringency.

For the empirical exercise, we decided to use a negative-binomial model. The main reason for doing so, is due to the peculiarities of patent data which, on the one hand, present a high amount of zero-values, and on the other, exhibit a high degree of over-dispersion which harms the equi-dispersion assumption of a Poisson distribution. It turns out that the initial suspicion can be confirmed that policy stringency indeed incentives firms to invest in in CCMTs. While the oversupply of EUA certificates discourages the deployment of those technologies, increasing stringency, introduced by the transition from Phase I to Phase II, motivates it. Respectively, a reduction of the oversupply from the mean oversupply in our sample to a balanced supply results in a 9% increase in patent counts for CCMTs on average. The shift from one phase to the other has had an even stronger effect on CCMTs resulting in a 35% increase of patent counts when controlling for external factors.

These results underline, that stringency is a core element in order to incentivize "green" innovation under a market-based policy. Nevertheless, these results lead directly to a next question, namely, how effective are CCMTs in helping to reach major policy goals such as the 20/20/20 headline targets for smart, sustainable and inclusive growth part of EU's 2020 climate and energy package.

In order to shed light on this question, Chapter 4 is untangling the effect of these technologies on two of the three headline targets. Technologies directly related to the energy sector are set in relation with gross inland energy consumption by fuel in order to measure to which extend CCMTs of the energy sector contribute to the achievement of a 20% share of renewables. On the other hand, overall CCMTs and CCMTs directed to the transport sector are related with overall final energy consumption and final energy consumption of the transport sector to measure their impact on the 20% increase in energy efficiency target. In this chapter, we employ a panel fixed effect approach with Driscoll-Kraay standard errors in order to control for fixed-country heterogeneity and cross-country dependency.

With respect to the former target, our analysis suggests that these technologies have a very clear positive impact on the share of renewables and a strong negative effect on energy consumption from petrol sources. Hence, CCMTs related to the energy sector can make a difference if the target of a 20% from renewables is met or not, and, additionally, help to reduce energy consumption from "conventional" sources. Concerning the latter goal, the impact of these technologies is still limited so far, especially, when comparing with the results obtained from the previous exercise. Moreover, the impact of CCMTs seems to vary greatly among sectors, i.e. a 10% increase in overall "green" patents led to a 0.28% decrease in total final energy consumption compared to a 0.123%

decrease in final energy consumption of the transport sector given a 10% increase of patents related to this sector.

The presented results, naturally, lead to a far reaching policy recommendations in order to, first, set the EU ETS back on track and, second, fostering the development and appliance of CCMTs. With respect to the former, the major issue is addressing the sizeable oversupply of certificates in the market and the resulting low price of allowances. The EU currently follows the strategy of "back-loading" meaning that a considerable amount of allowances is auctioned in a later stage in the third trading period. However, this approach does not lower the absolute value of allowances in the market, it only delays their market-introduction. A more promising approach taken by the EU is the creation of a market stability reserve, whereby unallocated allowances are transferred to it in order to guarantee a stable demand and supply of the same.

While this approach surely addresses the problem of excess supply, additional and, especially, more stringent market interventions could proof even more effective. Hence, the European Commission may consider the introduction of a price floor for emission certificates. Though, this represents a strong intervention in market dynamics, it would tackle two points at the same time. First, it provides security and clarity for companies affected by the policy in order to program their long-time emission reduction strategies. Second, a price floor assures robustness against external effects such as the impacts of an economic recession such as the one of 2008/2009. Thereby, policy makers need to have in mind, when setting such a floor, that it cannot be set too low in order to provide incentives for firms to lower their emissions but neither too high in order to not cause carbon leakage and a crowding-out of production and, ultimately, hampering the EU as a business and industry location. Since this is clearly a strong intervention which would be opposed by many stakeholders, a careful assessment of the pros and cons of the same is indispensable.

Furthermore, and to set the EU even more on it's a low-carbon economy trajectory, a tightening of emission caps is needed which as well tackles the problem of oversupply and provides additional incentives for firms to invest in "green" technology since it turned out that existing caps were set against inflated emission forecasts.

With respect to the development and appliance of new CCMTs, the EU should fortify policies such as the NER300 program and launch new ones as these technologies proof to be highly effective when it comes to climate change policy target achievement. Furthermore, not only should the EU focus on the development of these technologies but as well make sure that such technologies are applied and, hence, find their way into the production process.

Finally, the conclusions of the different empirical exercises and the resulting policy recommendations of this dissertation not only provide policymakers with reliable results and advice to improve existing policies but as well can be considered as a guide for future trading systems, such as the one in China, and additional climate change policies to come in order to avoid policy miss-designs and assure well-functioning of the same.

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