Innovation in climate change mitigation technologies and environmental regulation*

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1 Introduction

The scientific evidence for human induced climate change and environmental degradation is unequivocal (IPCC, 2014). The forecasted costs associated with global warming, the exhaustion of natural resources and air pollution are particularly alarmist. But, impacts of air pollution on human health are already salient. The World Health Organization (WHO) estimates that air pollution is now the world's largest single environmental health risk, being responsible for one in eight of total global deaths in 2012 (around 7 million deaths globally). According to the Lancet Commission on Pollution and Health, this number has increased to 9 million deaths in 2015. Air pollution is responsible for heart disease and stroke, lung cancer and respiratory diseases inter alia. Apart from health effects, air pollution also negatively affects key ecosystems, like forests or freshwater, and contributes to accelerate climate change.

Developing Climate Change Mitigation Technologies (CCMTs) is a key challenge to temper the costs associated with climate change and air pollution consequences (Nordhaus, 2007). As one of the main output of innovative activity, patents related to CCMT have grown extensively over the last decades. For example, according to Veefkind et al. (2012), the amount of patents published worldwide in "clean energy" has been multiplied by a factor of 4 between 1995 and 2008. In comparison, the total amount of patents applied during the same period has only doubled. Understanding the evolution of CCMTs is important in projecting the future impacts and costs of climate change and pollution-related activities. Our main goal in this paper is to investigate the impact of environmental policies implemented to decrease air pollution on innovation activities in general, and CCMTs in particular.

The Porter (1991) hypothesis, states that a well-designed environmental regulation can trigger innovation in more efficient technologies, which can more than offset regulatory costs and increase overall firms' competitiveness. The first part of the statement (the impact of the regulation on innovation) refers sometimes to the "weak" version of the Porter hypothesis, while the second part (the impact of the regulation on firms' performances) has often been characterized as the "strong" version of the assumption (see Ambec et al., 2013). Theoretical foundations of the Porter hypothesis rely on behavioral arguments, market failures, such as asymmetric information or Research and Development spillovers, or organizational failures (Ambec et al., 2013; see also Acemoglu, 2002).

On the empirical side, a large body of literature analyses the impact of environmental regulation on innovation (the "weak" version of the Porter hypothesis). These studies generally find a positive relationship between environmental policies and innovation (see Lajouw and Mody, 1996 for an early reference and Popp et al., 2010, for a recent review). However, there are major empirical challenges in determining the causal effect of environmental regulation on innovations. First, it is difficult to find an appropriate measure of environmental regulation (see *infra*). Second, the presence of third factors, including unobserved technology shocks, may influence both regulatory stringency and innovations. A pure reverse causality may also run from innovations to environmental regulations. This is true when relying on aggregate measures of technological change (at the country, or industry level). Two recent publications use micro(firm)-level data. Aghion et al. (2016) focus on the auto industry and show that firms tend to innovate more in "clean" technologies, such as electric or hybrid vehicles, when tax-inclusive fuel prices are higher. Moreover, they show that there is path dependence in the sense that firms that used to innovate in clean (resp. dirty) technologies in the past will also tend to innovate in clean (dirty) technologies in the future. Calel and Dechezleprêtre (2016) also use firm-level data and explore the impact of the European Union Emissions Trading system (EU-ETS) on the number of low-carbon patents. Using quasi-experimental techniques, comparing regulated and comparable non-regulated firms before and after the launch of the EU-ETS in 2005, they show that the EU-ETS increases the number of low-carbon patents among regulated firms by less than 10% (183 additional patents) and that this explains only 1% of the overall increase of low-carbon patenting because regulated firms only account for a small share of all patents. Using firm-level data offers several advantages as it allows to identify more specifically policy impacts. On the downside, it probably leads to an underestimation of the effect because the policy may also affect firms that are not directly covered by the regulation. In this paper, we identify the impact of the environmental regulation at the regional level, which seems to be the most appropriate level.

We also contribute to the existing literature and research by proposing an original variable that consistently evaluates changes in environmental regulation stringency. We focus on the main regulatory tool to fight air pollution in European Union (EU) Member States: the Ambient Air Quality Directive (AAQD) and its ancestor the Air Quality Framework Directive (AQFD) implemented in 1996. The AQFD and its daughter directives set numerical limits and thresholds for different types of pollutants and force countries to implement environmental measures in case of exceedance. In this paper, we construct an original variable that identifies, for every EU NUTS-2 region and year, exceedance of air quality limit values and reflects tougher environmental regulation. This proxy variable allows to tackle methodological problems pointed out in the literature (see Bagayev and Lochard, 2017). First, it partially solves the simultaneity problem because air quality limit values are the same for all Member States and are based on the WHO guidelines to protect human health. Second, considering the Air Quality regulation allows us to account for the multidimensions of environmental regulation because countries or regions might implement any policy or measure in the case of exceedance of air quality limit values.

The rest of the paper is organized as follows. Section 2 presents our empirical strategy, the identification and data. Then, in Section 3, we report our main results on the effect of environmental regulation on innovations and CCMTs in particular. Finally, in Section 4, we discuss our findings and detail our next steps.

2 Identification and Data

2.1 Empirical strategy

We implement a quasi diff-in-diff setting to test for the effect of environmental measures on innovation at the EU region (NUTS-2) level over the 1999-2015 period. The main assumption to be tested is that by increasing the cost of polluting activity, environmental measures should boost the incentive for environmentally-friendly innovations. Thus, we expect CCMT patenting activity to be disproportionately more affected in regions enforcing additional air pollution regulations. This conditional mechanism allows to implement a quasi diff-in-diff setting to test for the effect of environmental measures on innovation and include a wide range of fixed effects to control for omitted variables. The basic Poisson specification is as follows:

$$\begin{aligned} Patents_{r,c,t} &= \exp(\alpha_1(1-\delta)K_{r,c,t-1} + \alpha_2 RegAQ_{r,t} \times CCMT_c + \gamma_{r,t} + \gamma_{r,c} + \gamma_{c1,t}) \\ &+ \epsilon_{r,c,t} \end{aligned} \tag{1}$$

where $Patents_{r,c,t}$ is the count of patents in region r applied for a given technological class c and year t.[1] $(1-\delta)K_{r,c,t-1}$ is the region's knowledge capital as given by the stock of patents on the previous period depreciated by a rate δ (in logarithm).[2] $RegAQ_{r,t}$ is the measure of a region's environmental regulation change due to the exceedance of a given pollutant concentration as imposed by the EU Air Quality Directive (see Section 2.2), and $CCMT_c$ is a dummy variable capturing the class of patents pertaining to the "technologies or applications for mitigation or adaptation against climate change", i.e. the class Y02 (see Section 2.3). In further refinements of our results, we study how regulations related to different pollutants affect different

[1] All variables and sources are defined in the Appendix (Table 8).

[2] Stocks are constructed using the perpetual inventory method with knowledge depreciation rate set at 20% (e.g. Aghion et al., 2016). The value of a given patent is set to zero after 20 years. We also add a dummy variable to account for observations with a lagged stock of innovations of zero.

sub-classes of CCMTs. $\gamma_{r,c}$ are technological class-region fixed effects, $\gamma_{r,t}$ are region-year fixed effects and $\gamma_{c1,t}$ are class (one digit)-year fixed effects. These fixed effects are crucial to control for regional specialization in innovative activity, regional trends and shocks and technological trends and shocks common to all regions. Finally, $\epsilon_{r,c,t}$ is the usual error term.

Equation (1) allows to compare specialisation in CCMTs (CCMTs vs non-CCMTs) of regions that implement additional environmental measures and specialisation of similar regions that don't. The coefficient of interest, α_2, measures any difference between the two after controlling for all major innovation determinants at the regional level that can be therefore attributed to the environmental regulation. We further test the robustness of our results by estimating our model on different sub-samples and by introducing additional control variables varying at the region-class-year (r, c, t) level (see Section 3.2).

Because our dependent variable is a count of patents, we use a Poisson model and a high-dimensional fixed effects procedure extended to non-linear models (Guimaraes and Portugal, 2010).

2.2 Proxy for environmental regulation

Our proxy variable for environmental regulation is based on the Ambient Air Quality Directive (2008/50/EC). The AAQD is the main regulation to fight air pollution in EU Member States. It sets numerical limits and thresholds for the most prevalent air pollutants and force EU countries to implement environmental measures in case of exceedance. Eight pollutants are considered in this Directive: sulphur dioxide (SO2), nitrogen oxides (NOx), lead (Pb), particulates (PM), carbon monoxide (CO), benzene (C6H6), ozone (O3) and fine particulate matter (PM2.5) (see Table 9 in

Appendix).[3]

The general principles of the regulation are as follows. For the purposes of air quality assessment and monitoring, Member States have to define geographical areas within their territories. These zones include all agglomerations with a population of 250,000 inhabitants and generally correspond to administrative regions. Air pollution concentration is measured by more than 4,000 stations located in these regions and distributed across the EU. The AAQD then requires Member States to draw up and report detailed plans and programs for zones in which at least one pollutant exceeds its limit value in order to fall below the limit value. These measures include medium or long-term actions, such as the development of environmentally-friendly innovations, as well as short-run actions (e.g. suspensions or restrictions of polluting activities contributing to the non-attainment, traffic restrictions) (see also Bagayev and Lochard, 2017 for a detailed description of the regulation).

We focus here on compliance with limit values for three major pollutants: particulates (PM10), nitrogen dioxide (NO2) and Ozone (O3) for several reasons. First, they represent the target of most (79%) air quality plans implemented since 2004 (see also EEA, 2018a).[4] Environmental measures focus mainly on NO2 (43% of air quality plans), followed by PM10 (25%) and O3 (11%).[5] Second, these three

[3]The AAQD merges the preceding Directive, the Air Quality Framework Directive (1996/62/EC) implemented by the EU in 1996 and its three first 'daughter' directives which entered into force in 1999, 2000 and 2002. It also sets a new air quality objective for fine particulate matter (PM2.5) and allows for time extensions for given zones for PM10, NO2 and C6H6. A fourth 'daughter' directive (2004/107/EC) which sets objectives for Arsenic, Cadmium, Nickel and Benzo(a)pyrene is not resumed in the AAQD.

[4]Under the EU Air Quality Directive, Member States have to report on the plans and measures they implement and these plans and measures are made available by the European Environment Agency under the Air Quality e-Reporting (Air Quality plans, data flow H). Other pollutants represent the target of less than 5% of air quality plans (PM2.5: 4.8%, BaP: 3.8%, SO2: 2.5%, CO: 2.3%).

[5]There might be fewer measures targeting ozone exceedances for two main reasons. First, ozone is a secondary pollutant coming from the reaction of nitrogen dioxides and volatile organic compounds in the presence of sunlight and may happen away from emission sources. Therefore, measures needed in case of exceedance may involve several municipalities, regions or even countries. Second, under the Air Quality Directive, the ozone standard is a 'target value' (and not a 'limit value') and therefore not legally binding (see below and EEA, 2018b).

pollutants are the ones that are the most reported by monitoring stations (73% of all stations-years over 1999-2015 for NO2; 62% for PM10 and 55% for O3). Except for sulphur dioxide (SO2) reported by 53% of stations-years, all other pollutants are reported by less than 30% of stations-years. However, we do not focus on compliance with limit values for SO2 because in recent years, SO2 concentrations are generally well below the limit values in all EU countries.[6] NO2 emissions and Particulates come from various economic sectors. The largest contributor to NO2 emissions is road transport (39% in 2015), followed by energy production and distribution (19%), commercial, institutional and households fuel combustion sector (14%), and energy use in industry (12%). PM10 emissions mainly come from commercial, institutional and households fuel combustion sector (42%), followed by industrial processes and product use (17%) and agriculture (15%) (EEA, 2017).

An important characteristic of the AAQD is that these limit values are legally binding, meaning that judicial actions may be undertaken if a Member State fails to comply with the regulation. Moreover, the European Commission oversees the implementation of EU legislation and can launch legal proceedings, including enforcement measures against Member States that do not comply with the AAQD requirements. The European Commission currently pursues infringement proceedings on NO2 and PM10 against respectively 13 and 16 Member States. Most cases are settled before being referred to the European Court of Justice, which means that the Commission considers that Member States' replies are satisfactory or that they comply with the requests.[7] However, for PM10, five countries have been recently referred to the Court of Justice (Hungary, Italy, Romania, Bulgaria and Poland).

[6] For instance, only eleven regions out of 273 (0.4%) from 6 EU countries registred concentrations above the daily limit value for SO2 at least once over the period 2010-2015 (see also EEA, 2017).

[7] The infringement procedure is the following. The Commission addresses a 'Letter of Formal Notice' to the Member State requesting an answer within two months. Depending on the reply, the Commission may decide to address a second letter ('Reasoned Opinion') (once again with a reply within 2 months) and if the Member State does still not comply with the requests, the case may be referred to the Court of Justice. If the country still does ot comply with the decision of the Court, the Commission may refer the country back to the Court and in this case proposes financial penalties.

For these last two countries, the Court has already handed down judgments, considering that they breached the law. For NO2, three countries have been referred to the Court of Justice in 2018 (France, Germany and the United Kingdom). As a robustness check, we will exclude these countries from the sample, considering that these countries have not fully implemented environmental measures in order to comply with the regulation (see Section 3.2).

Measures to encourage or enforce compliance also rely on peer pressure and pressure from citizens and environmental organisations because the directive require Member States to inform the public about the assessment and management of air quality. Very recently, the European Environment Agency (EEA) and the European Commision have launched a European Air Quality Index in order to give "citizens an easy way to access information on their local air quality" (Hans Bruyninckx, EEA Executive Director).

Finally, even if each Member State is responsible for implementing adequate measures in case of exceeding, most environmental measures are implemented at the regional level. Among the 51,530 measures reported for the years 2012 to 2016, 86% are local or regional (and 14% national).[8] Therefore, in our empirical analysis, we consider the regional level as the most appropriate because environmental measures and constraints faced by firms are essentially perceived at this level.

We focus on exceedances of limit values for three main pollutants (NO2, PM10 and O3) as a proxy for change in environmental stringency. More precisely, we construct, for each NUTS-2 region and year, an original variable (RegAQ) that measures, with a dummy variable, exceedances of air quality limit values for each pollutant and zero otherwise (limit values are displayed in Table 9 in Appendix). We also compute for each region and year a synthetic dummy variable that measures exceedances of air quality limit values for any pollutant (NO2, PM10 or O3). These variables do

[8]Source: EEA, Air quality measures (data flow K).

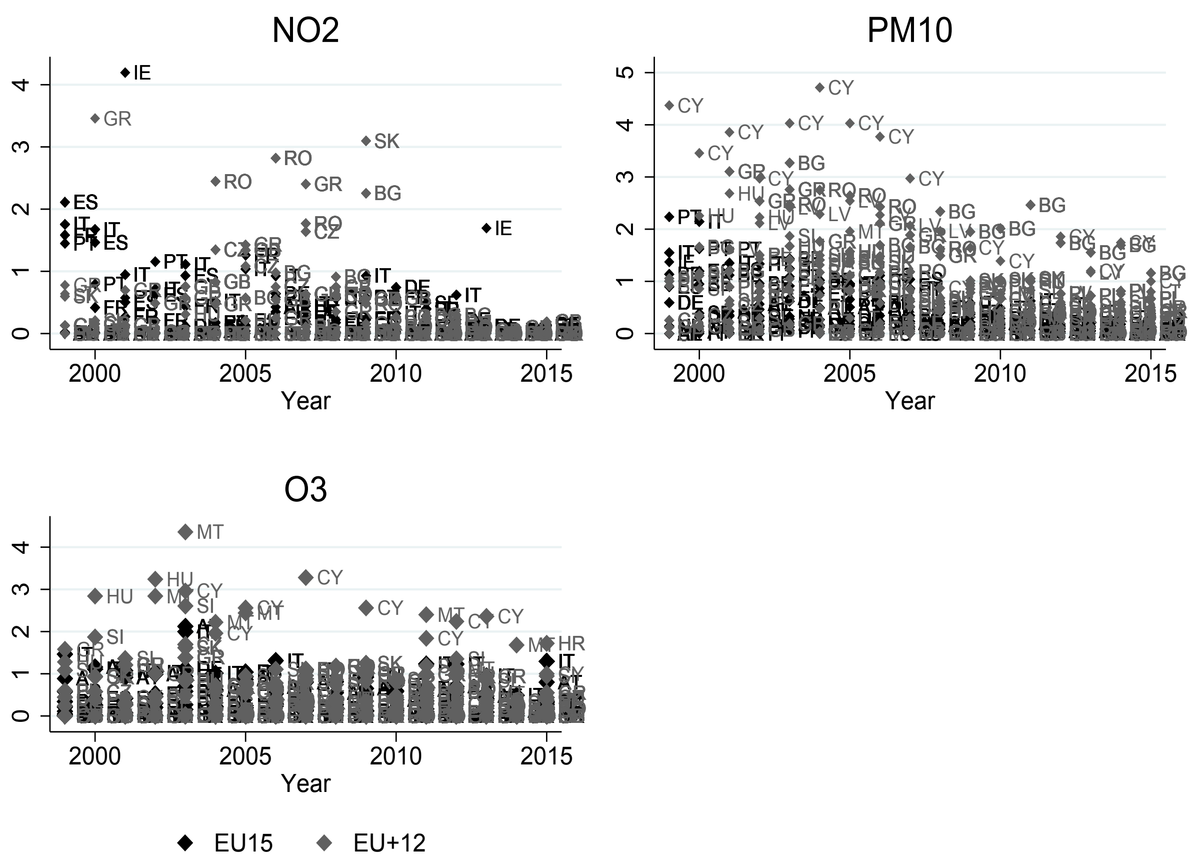
not aim to measure the overall level of environmental policy stringency, but rather *additional* environmental measures implemented by EU countries to comply with the AAQD. In our empirical estimations, we also use two alternative variables for RegAQ. The first one is the share of stations in each region and year that are in exceedance (in the total number of stations per region and year). The second one is the average exceedance level above the limit value (average number of days or times of exceedance by region and year) over the allowed level.[9] These two variables intend to measure the magnitude of exceedances, which should correlate with the stringency of the regulation.

Figure 1 displays the average number of exceedances of limit values over allowed ones by country and year for our three main pollutants (NO2, PM10 and O3). It shows that, over our period of time (1999-2015) several countries, including both old and more recent EU countries have at least one exceedance above the limit value and therefore should have implemented additional environmental measures in at least one region to comply with the regulation. The number of exceedances over allowed ones also decrease over time for the three pollutants.

These proxy variables for environmental regulation has several advantages. It allows us to tackle two major problems, i.e., simultaneity and multidimensionality, that have been widely documented in the literature (e.g. Levinson and Taylor, 2008). First, the ambient air quality limits we consider are equally and uniformly imposed on all EU countries and are based on considerations related to the protection of human health. Thus, all Member States face the same limit values, which are exogenous to their own economic activity or preferences (lobbying from citizens or industrial sectors). Second, environmental regulation is multidimensional and governments use many different instruments in order to achieve their objectives

[9]For example, the hourly limit value for NO2 is 200μg/m3 not to be exceeded more than 28 times a year (see Table 9 in Appendix). In 2010, six stations of the Madrid region in Spain have exceeded more than 28 times. The average number of times of exceedances for this region and year is 42.88, so that our RegAQ variable in this case is equal to 1.38 ($= (42.88 - 18)/18$)

Figure 1: Intensive regulation (average number of days/times of exceedance over the allowed level) by country and year



Source: AirBase (EEA) and authors' calculations.

(Brunel and Levinson, 2013). Here, we do not focus on one particular measure, such as the lead content of gasoline or eco-taxation. Indeed, within the AAQD framwork, Member States have high flexibility in implementing adequate measures to reduce emissions below the limits imposed by the directives. On the downside, our proxy for environmental regulation does not allow to compare the effects of different policy instruments on clean innovations (see e.g. Veugelers, 2012).

Figure 2: Mean indices of annual regional pollutants concentration for ‘regulated’ and ‘non-regulated’ regions (index 100 in 2000)

Source: AirBase (EEA) and authors’ calculations. ‘Regulated regions’ are defined as regions that exceeded at least once over the period 2000-2015 and ‘non-regulated’ as regions that never exceeded over the same period.

Furthermore, the AAQD is relatively effective and most regions and countries do implement environmental measures in case of exceedances. To provide some indirect evidence that the regulation is enforced sucessfully, we compare the mean indices of annual regional pollutants concentration for ‘regulated’ regions (i.e. regions that have to implement environmental measures because they exceeded at least once over the period 2000-2015) and 'non-regulated' regions (regions that never exceeded over the same period). Figure 2 shows that the decrease in annual concentration in 'regulated' regions is larger than the decrease in 'non-regulated' regions for NO2 and PM10. Concentrations of NO2 began to decrease in 2010 (date of entry into force of the limit value) and decreased only in regulated regions, as compared to their value in 2000. Concentration trends of PM10 are very similar for regulated and non-regulated regions until 2006 (one year after the entry into force of the limit value) and then began to diverge, with a larger decrease in regulated regions. For O3, there is no decreasing trend and no clear difference between regulated and unregulated regions. This is not surprising given that ozone is a secondary pollutant, depending heavily on meteorology in a given year and that fewer environmental measures generally target this pollutant (see above). Overall, this figure provides some evidence that the regulations are enforced successfully (at least for NO2 and PM10).

Last but not least, the AAQD is the most constraining legislation as compared to other EU directives. The other major legislation dealing with air quality, the National Emission Ceilings Directive (NECD) adopted in 2001 sets emission ceilings specific to each member state for four pollutants (SO2, NOx, COV and NH3) that have to be met in 2010.[10] For the three pollutants that we consider here, only NOx appears in both directives. Moreover, most countries have met their national emission ceilings for NOx during the period 2010-2015 and only Austria and Ireland persistently exceeded their respective ceilings. In robustness checks, we will control for potential measures unrelated to AAQD but related to NECD (see Section 3.2). Note that there are also specific emission standards coming from other directives (such as the Industrial Emissions Directive or the Medium Combustion Plant Directive) but they are source- or product-related and generally support the targets of the AAQD and NECD.

[10]The revision of the NECD in 2016 adds a fifth pollutant (PM2.5) and sets new emission reduction commitments for 2020 and 2030.

2.3 Patents data

Patent data have been used extensively as a measure of technological innovation. This measure has both pros and cons, as compared to alternative measures, such as R&D expenditures or the R&D personnel (e.g. OECD, 2009; Dechezleprêtre et al., 2011). On the one hand, as a way of protecting inventions, patents are a natural measure of the output of the innovation process (Griliches, 1990). Moreover, they provide a detailed information on the nature of the inventions, the inventor, their technological content and geographical locations among other things. On the other hand, patents capture only one way for firms, institutions or individuals to protect inventions. Patents' values are also quite heterogenous, some patents having high value, while others could remain unexploited.

Following the recent literature, we proxy for the innovation change in a given technological class by the number of patents applied in this class. For the purpose of our empirical strategy, we use patent data information at the EU NUTS-2 level broken down by technology class. These data come from the European Patent Office (EPO) Worldwide Patent Statistical Database (PATSTAT). Patents are classified using the Cooperative Patent Classification (CPC). We use annual counts of patent applications at the EPO (whether granted or not) at the 4-digit technology class level based on the date of priority. We follow the literature and consider only EPO patents (and not patents exclusively filed with national patent offices) in order to ensure that the patents that we consider are of high quality (see e.g. Calel and Dechezleprêtre, 2016).[11]

To avoid double counting, we follow common practice and use fractional counting. If a patent is assigned to several CPC codes, we divide equally the patent among all CPC codes. We also use information on the region of residence of the inventor

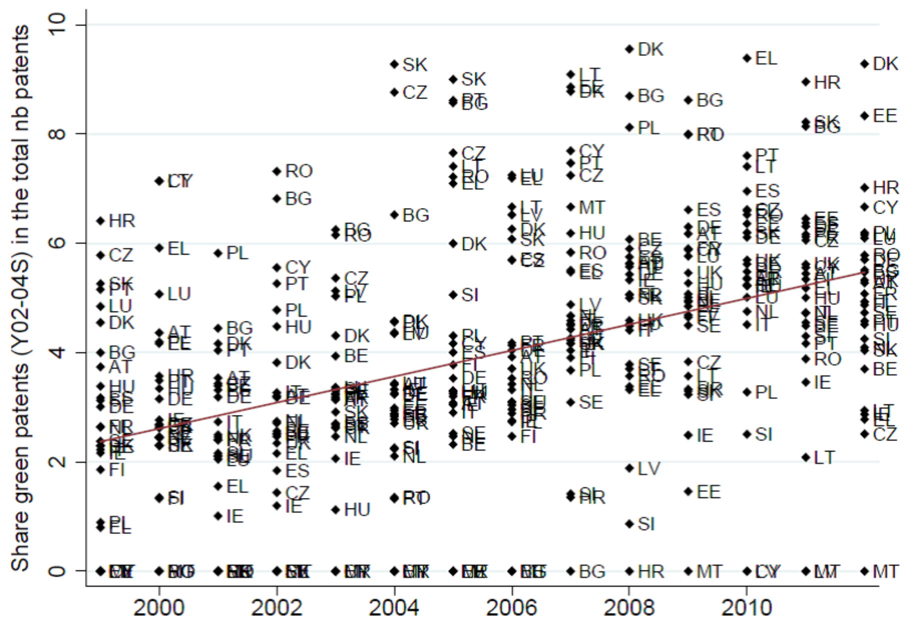
[11] As argued by Calel and Dechezleprêtre (2016), only high-value inventions typically get patented at the EPO.

to capture geographical distribution of patents. As before, if a patent has several inventors localised in several EU regions, we divide equally the patent among all regions. In the final sample, we have patents in 654 CPC classes (4 digits) for 273 regions in 28 EU countries over the period 1999-2015.

To measure the direction of technological change and identify innovations that should foster climate change mitigation, we rely on the recently developed class pertaining to "technologies or applications for mitigation or adaptation against climate change" (Veefkind et al., 2012). This new category - the Y02 class - has been developped by means of search strategies by experienced expert examiners and formalized into algorithms. It consistently applies to patents filed during our period of investigation (and before). The Y02 class now includes eight different sub-classes and allows for a detailed analysis of the environmental measures impact on different types of CCMT innovations. The eight sub-classes are defined as follow: Y02A (Adaptation to climate change), Y02B (Buildings), Y02C (Capture and storage of greenhouse gases) , Y02D (ICT aiming at the reduction of own energy use), Y02E (Production, distribution and transport of energy), Y02P (Industry and agriculture), Y02T (Transportation) and Y02W (Waste and wastewater) (see Table 10 in Appendix). In our empirical analysis, we have all categories except Y02A and Y02D which are too recent. Note that there is another category, Y04S, which relates to smart grids. This Y02/Y04S tagging scheme is the most comprehensive and accurate one and it has been used in several recent papers focusing on clean innovations (e.g. Calel and Dechezleprêtre, 2016).

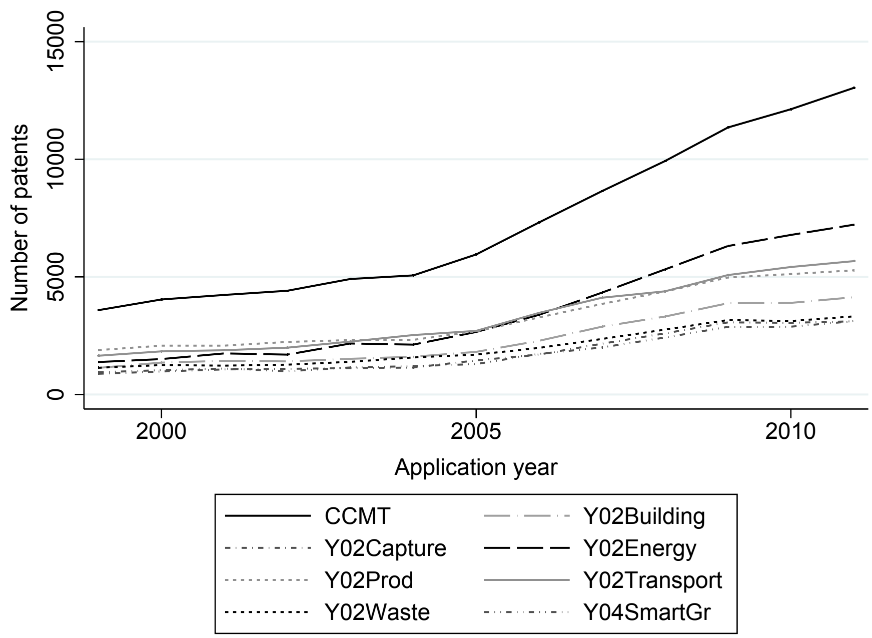
The share of CCMTs in the total number of patents is now about 5% in Europe and it has steadily increased since 1999, in particular for the Y02E sub-class (see Figures 3 and 4). This sub-class (Y02E, clean energy) now represents the largest class in the number of patents, followed by CCMTs in transportation (Y02T) and in industry and agriculture (Y02P) (Figure 4).

Figure 3: Average share of CCMTs (Y02-Y04S) in the total number of patents by country and year (%)



Source: PATSTAT. The number of patents is computed using fractional counting (see text for details).

Figure 4: Evolution of the number of CCMT patents over the period 1999-2013



Source: PATSTAT. The number of patents is computed using fractional counting (see text for details).

The share of CCMTs in the total of patents also varies largely across EU countries, with a larger value than the average in Nordic countries, such as Denmark specialized in wind energy, but also in some Southern or Eastern European countries, such as Greece or Romania specialized in solar energy (Figure 3).

This large variability is also reflected in the share of patents in different CCMTs (Building, Capture, Energy, Industry, Transport, Waste and Smart Grids) in the total number of patents in CCMTs (see Table 1). For instance, Denmark, Greece and Cyprus are highly specialized in clean energies as compared to other CCMTs, while France, Germany and Sweden are specialized in CCMTs related to transportation. This Table also shows that some Eastern European countries, such as Slovakia, the Czech Republic and Lithuania file relatively more patent applications in CCMTs in waste and wastewater than the average.

3 Empirical results

We will first present our baseline results, followed by some robustness checks and additional findings.

3.1 Baseline results

In our empirical analysis, we first estimate our baseline equation (eq. 1) using a Poisson estimator on the overall sample including 273 regions, 654 technological classes and 17 years (1999-2015). To capture a change in environmental regulation we first introduce a dummy variable indicating whether pollutants' concentration exceed the limit value in a given region and a given year (see section 2.2). Estimation results are displayed in Table 2. The interaction between this dummy avariable and a dummy variable for CCMTs (the Y02/Y04S class) thus capture the effect of

Table 1: Share of patents in different CCMTs in the total number of patents in CCMTs

Country	Total nb Pat. in CCMTs (1)	YBuilding (2)	YCapture (3)	YEnergy (4)	YProd (5)	YTransport (6)	YWaste (7)	YSmartGr (8)
Austria	578,198	19.0	0.9	25.5	22.9	18.7	11.4	1.4
Belgium	520,872	10.8	0.9	23.3	**36.8**	15.3	11.4	1.5
Bulgaria	8,482	3.7	0.0	34.7	36.1	21.9	1.3	2.4
Cyprus	3,518	11.3	0.0	**52.8**	15.5	5.5	11.9	3.0
Czech Republic	49,073	15.7	0.3	23.4	30.5	7.7	**18.7**	**3.8**
Germany	9,848,394	10.9	1.4	27.6	22.6	**31.1**	4.7	1.7
Denmark	679,472	10.4	0.9	**56.7**	22.8	4.5	4.0	0.7
Estonia	10,607	20.1	0.0	47.4	21.7	2.7	8.1	0.0
Greece	28,613	11.5	0.0	**54.2**	14.5	8.9	10.6	0.2
Spain	430,583	11.8	0.8	44.3	23.9	10.2	7.9	1.0
Finland	346,673	29.0	0.4	21.3	27.7	12.5	7.7	1.4
France	2,591,430	11.8	**2.2**	25.0	19.5	**32.8**	7.1	1.5
Croatia	6,446	13.8	0.0	21.5	**38.4**	15.0	11.3	0.0
Hungary	45,512	**30.9**	0.6	12.2	28.1	17.1	11.1	0.1
Ireland	79,849	**33.9**	0.7	29.9	17.4	3.7	13.2	1.1
Italy	1,068,835	17.6	1.3	25.7	27.5	17.7	8.5	1.7
Lithuania	3,728	7.6	0.0	23.3	30.9	8.7	**23.1**	**6.5**
Luxembourg	40,829	7.9	1.9	18.3	33.9	27.7	10.3	0.0
Latvia	7,096	3.4	0.0	39.1	**48.9**	0.0	8.6	0.0
Malta	1,490	25.0	0.0	25.0	25.0	25.0	0.0	0.0
Netherlands	932,443	**30.6**	**3.8**	25.4	28.4	5.8	5.1	0.9
Poland	78,816	12.1	0.6	22.5	30.4	15.5	15.2	**3.7**
Portugal	31,585	17.3	**2.3**	25.9	35.4	7.9 1	0.8	0.4
Romania	12,747	26.3	1.0	42.6	17.1	9.4	3.6	0.0
Sweden	704,250	23.2	0.8	25.2	16.8	**28.4**	3.8	1.7
Slovenia	15,498	21.7	0.0	29.8	36.6	9.5	1.6	0.8
Slovakia	11,757	14.6	0.0	36.8	21.0	3.9	**22.8**	0.9
United Kingdom	1,390,141	17.1	2.1	29.3	20.3	22.4	6.5	2.3
Average	-	16.7	0.8	31.0	26.8	13.9	9.3	1.4

Notes: The total number of patents in CCMTs over the period 1999-2015 (column 1) and the average share of patents in different CCMTs in the total number of patents in CCMTs are computed using fractional counting (see text for details). The three largest shares are marked in bold.

measures implemented to comply with the environmental regulation on the specialisation of regions in CCMTs. In columns (1) and (2) we use a synthetic variable ('Any Pollutant') that indicates whether any pollutants' concentration (PM10, NO2, O3) exceeds the limit value. In the remaining columns, we use a specific dummy variable for PM10 exceedances (columns 3 and 4), NO2 exceedances (columns 5 and 6) and O3 exceedances (columns 7 and 8).

We find that the stock of patents in a given technological class has the expected positive effect and it is significant at the 1% level in all cases. These first results also indicate that regions implementing environmental measures in order to comply with the regulation do not generally tend to innovate more in CCMTs (columns 1, 3 and 7 of Table 2). Indeed, the only pollutant for which there is a positive impact of the regulation on innovation specialisation is NO2 (column 5).

However, when we disaggregate CCMTs into different sub-classes (columns 2, 4, 6 and 8) we obtain stimulating results. Regions that implement additional environmental measures tend to innovate more in energy sources alternative to fossil fuels (Y02E), in smart grids (Y04S), and to some extent, in capture and storage of greenhouses gases (Y02C). But, they seem to innovate less in CCMTs in energy intensive industries (Y02P) and in waste and wastewater (Y02W). It seems therefore that air pollution regulations in EU regions tend to foster some CCMTs while depressing others (as compared to innovations that are not CCMT).[12]

In the following sections, we adress this diverging observed impacts in different technology fields and provide several interpretations (see Section **??**.

In a second step, we use two alternative intensive variables that measure the stringency (the intensity) of environmental measures: the share of stations in each region

[12]Note that our model specification only allows to estimate the impact of environmental regulations on CCMTs as compared to non-CCMTs. It does not allow to estimate the global effect of environmental regulations on innovations because in this case the $ReqAQ_{rt}$ variable would be collinear with region-year fixed effects.

Table 2: Environmental regulation (dummy) and CCMTs at the region level

	Any Pollutant		PM10d		NO2h		O3	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$RegAQ_{rt} \times Y$	-0.0103		0.0110		0.0554**		-0.00319	
	(0.0189)		(0.0178)		(0.0239)		(0.0215)	
$RegAQ_{rt} \times$YBuilding		-0.00526		0.0575		0.0150		-0.0314
		(0.0385)		(0.0397)		(0.0704)		(0.0456)
$RegAQ_{rt} \times$YCapture		0.0809		-0.000363		0.326**		0.217*
		(0.0897)		(0.0638)		(0.0321)		(0.0649)
$RegAQ_{rt} \times$YEnergy		0.213***		0.206***		0.297***		0.200***
		(0.0293)		(0.0291)		(0.0416)		(0.0337)
$RegAQ_{rt} \times$YProd		-0.222***		-0.155***		-0.123***		-0.220***
		(0.0324)		(0.0326)		(0.0413)		(0.0363)
$RegAQ_{rt} \times$YTransport		-0.0341		-0.0345		-0.0401		-0.0380
		(0.0330)		(0.0316)		(0.0414)		(0.0250)
$RegAQ_{rt} \times$YWaste		-0.351***		-0.277***		-0.111		-0.242***
		(0.0456)		(0.0488)		(0.0891)		(0.0676)
$RegAQ_{rt} \times$YSmartGr		0.216***		0.111		0.649***		0.324***
		(0.0793)		(0.0871)		(0.128)		(0.0826)
$\ln Patents\ Stock_{rct-1}$	0.154***	0.153***	0.154***	0.153***	0.154***	0.153***	0.154***	0.153***
	(0.00978)	(0.00976)	(0.00978)	(0.00977)	(0.00976)	(0.00978)	(0.00978)	(0.00978)
Observations	1,217,060	1,217,060	1,217,060	1,217,060	1,217,060	1,217,060	1,217,060	1,217,060
Region-class FE	yes	yes	yes	yes	yes	yes	yes	yes
Region-year FE	yes	yes	yes	yes	yes	yes	yes	yes
Class-year FE	yes	yes	yes	yes	yes	yes	yes	yes

Notes: The dependent variable is the weighted counts of patents per EU region and year. Robust standard errors clustered at the region-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1. The regression includes a dummy variable to account for observations with a lagged stock of innovations of zero (unreported).

and year that are in exceedance (in the total number of stations per region and year) (columns 1, 3 and 5 of Table 3) and the average exceedance level above the limit value (average number of days or times of exceedance by region and year) over the allowed level (columns 2, 4 and 6 of Table 3). Estimations results provide similar conclusions as before. There seems to be a diverging impact of the regulation in different technology fields. Regions implementing environmental measures seem to innovate more in renewable energies (Y02E) (as compared to non-CCMTs) but less in CCMTs in energy intensive industries (Y02P) and in waste and wastewater (Y02W) (as compared to non-CCMTs).

3.2 Robustness analysis

We perform several robustness checks in order to test the sensitivity of our results. We report only robustness results using our dummy for the regulation variable ($RegAQ_{rt}$) but estimation results using the alternative intensive variables (share of exceeding stations and average exceedance levels above the limit value) give similar conclusions.

We first estimate our model on individual countries, selecting the five EU15 countries that are the largest in terms of numbers of regions (France, Germany, Itay, UK, Spain).[13] Results are reported in Appendix (Table 11). For almost alll countries, our results reveal the same pattern as before. We find that regulated regions in every of these five countries (except the UK) innovate more in CCMTs related to the production, distribution or transport of energy (Y02E) (as compared to non-CCMTs), while they innovate less in CCMTs in energy intensive industries (Y02P) and in CCMTs in waste and wasterwater (Y02W) (except for Spanish regions).

[13]The first four countries are also the largest ones in terms of total numbers of patents and Y02/Y04S patents over our period of time (1999-2015). Spain holds the tenth position in terms of the total number of patents (over 28).

Table 3: Environmental regulation (intensive measures) and CCMTs at the region level

	PM10d		NO2h		O3	
	Sh.Stations	Ex.Level	Sh.Stations	Ex.Level	Sh.Stations	Ex.Level
	(1)	(2)	(3)	(4)	(5)	(6)
$RegAQ_{rt}$×YBuilding	-0.00284	0.0625	-0.711	0.00281	-0.133	-0.00494
	(0.102)	(0.0418)	(0.553)	(0.00910)	(0.136)	(0.0561)
$RegAQ_{rt}$×YCapture	-0.0785	-0.186***	2.249*	0.0373**	0.656	0.407**
	(0.368)	(0.0717)	(1.272)	(0.0154)	(0.492)	(0.186)
$RegAQ_{rt}$×YEnergy	0.313***	0.163***	2.396***	0.0363***	0.436***	0.177***
	(0.0993)	(0.0370)	(0.438)	(0.00734)	(0.0965)	(0.0423)
$RegAQ_{rt}$×YProd	-0.625***	-0.182***	-1.713***	-0.0177***	-0.691***	-0.340***
	(0.0987)	(0.0376)	(0.452)	(0.00611)	(0.128)	(0.0618)
$RegAQ_{rt}$×YTransport	-0.206**	-0.0929*	-0.681*	-0.00546	-0.220*	-0.0867
	(0.0934)	(0.0478)	(0.348)	(0.00452)	(0.127)	(0.0608)
$RegAQ_{rt}$×YWaste	-0.768***	-0.183***	-2.525***	-0.00336	-0.518**	-0.300***
	(0.158)	(0.0525)	(0.954)	(0.0275)	(0.245)	(0.0862)
$RegAQ_{rt}$×YSmartGr	-0.0472	-0.104	4.589***	0.0589***	0.716**	0.279**
	(0.304)	(0.0979)	(1.607)	(0.0135)	(0.285)	(0.127)
$\ln Patents\ Stock_{rct-1}$	0.513***	0.514***	0.513***	0.514***	0.513***	0.513***
	(0.00977)	(0.00977)	(0.00976)	(0.00977)	(0.00978)	(0.00978)
Observations	1,217,060	1,217,060	1,217,060	1,217,060	1,217,060	1,217,060
Region-class FE	yes	yes	yes	yes	yes	yes
Region-year FE	yes	yes	yes	yes	yes	yes
Class-year FE	yes	yes	yes	yes	yes	yes

Notes: The dependent variable is the weighted counts of patents per EU country and year. Robust standard errors clustered at the region-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1. The regression includes a dummy variable to account for observations with a lagged stock of innovations of zero (unreported).

Note that patents stocks are less significant for Spain and Italy because of the lower number of observations.

We also estimate our model by excluding from the original sample one CPC class (1 digit) at a time. Table 12 in Appendix (columns 1 to 8) shows that our estimation results do not depend on a specific technology class. In all cases, we find that regulated regions tend to innovate more in clean energy and smart grids (Y02E and Y04S) as compared to non-CCMTs, but less in energy intensive industries and in waste and wasterwater (Y02P and Y02W).

We then estimate our model on several sub-samples to test the robustness of our results with respect to the environmental regulation variable. We first exclude regions that never exceeded over the whole time span (1999-2015). These regions are used in the control group in our baseline estimations but we might think that they are intrinsiquelly different from the regions that exceeded at least once. On our original sample, we have 273 regions. Among these 273 regions, 63 regions from 11 countries never exceeded. These regions are located mainly in the UK for 52% and in Greece for 11%. When we exclude these regions that did not have to implement any environmental measures to comply with the AAQD because they never exceeded limit values, we estimate a sort of 'treatment effect among the treated'. Results are displayed in column 1 of Table 4. They are very close to the baseline estimates (column 2 of Table 2).

We further investigate the robustness of our results with respect to the *RegAQ* variable. Other regulations than the AAQD at the EU, national or sub-national levels are controlled for in the estimation with region-year fixed effects. However, if these other regulations are correlated with AAQD exceedances (our measure of the regulation), then our estimated coefficient of interest might be biased. There is no objective reason why this should happen in the case of a regulation that has nothing to do with the Air Quality Directive. However, we still want to check the

Table 4: Robustness checks - Regulation (dummy) and innovations at the region level

	Any Pollutant Without Non-Exc Reg. (1)	Any Pollutant No NECD Exc. (2)	Any Pollutant No Infringements (3)	PM10d With Polut. level (4)	NO2h With Polut. level (5)	O3 With Polut. level (6)
$RegAQ_{rt}$×YBuilding	0.0122	0.409***	0.0556	0.0658*	0.00869	-0.0360
	(0.0392)	(0.105)	(0.0659)	(0.0394)	(0.0707)	(0.0457)
$RegAQ_{rt}$×YCapture	0.0959	-0.109	-0.200	0.0532	0.317**	0.215*
	(0.0899)	(0.256)	(0.147)	(0.0938)	(0.135)	(0.120)
$RegAQ_{rt}$×YEnergy	0.225***	0.352***	0.195***	0.209***	0.291***	0.194***
	(0.0305)	(0.0914)	(0.0527)	(0.0292)	(0.0424)	(0.0337)
$RegAQ_{rt}$×YProd	-0.200***	-0.357***	-0.0440	-0.137***	-0.109**	-0.207***
	(0.0328)	(0.0956)	(0.0697)	(0.0326)	(0.0434)	(0.0357)
$RegAQ_{rt}$×YTransport	-0.0170	-0.0464	0.0433	-0.0592*	-0.0395	-0.0408
	(0.0338)	(0.0998)	(0.0796)	(0.0346)	(0.0404)	(0.0354)
$RegAQ_{rt}$×YWaste	-0.324***	-0.222**	-0.390***	-0.257***	-0.112	-0.227***
	(0.0461)	(0.110)	(0.106)	(0.0506)	(0.0894)	(0.0687)
$RegAQ_{rt}$×YSmartGr	0.230***	0.0608	0.0567	0.141	0.630***	0.334***
	(0.0796)	(0.211)	(0.199)	(0.0902)	(0.130)	(0.0841)
ln $MeanPol$×YBuilding				-0.00562	-0.0684	0.114
				(0.110)	(0.0947)	(0.205)
ln $MeanPol$×YCapture				-0.543**	-0.115	0.102
				(0.257)	(0.295)	(0.579)
ln $MeanPol$×YEnergy				-0.386***	-0.0795	0.127
				(0.0887)	(0.0848)	(0.171)
ln $MeanPol$×YProd				0.741***	0.351***	-0.635***
				(0.0932)	(0.0971)	(0.160)
ln $MeanPol$×YTransport				-0.00203	-0.134	-0.0259
				(0.114)	(0.0910)	(0.201)
ln $MeanPol$×YWaste				0.720***	0.00703	-0.530**
				(0.145)	(0.159)	(0.270)
ln $MeanPol$×YSmartGr				-0.845***	-0.362	-0.789*
				(0.256)	(0.237)	(0.465)
ln $Patents\ Stock_{rct-1}$	0.172***	0.00992	0.127***	0.129***	0.154***	0.155***
	(0.0113)	(0.0154)	(0.0207)	(0.0109)	(0.0101)	(0.0101)
Observations	922,130	220,205	353,039	1,076,044	1,156,816	1,144,997
Region-class FE	Yes	Yes	Yes	Yes	Yes	Yes
Class-year FE	Yes	Yes	Yes	Yes	Yes	Yes
Region-year FE	Yes	Yes	Yes	Yes	Yes	Yes

Notes: The dependent variable is the weighted counts of patents per EU country and year. Robust standard errors clustered at the region-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1. The regression includes a dummy variable to account for observations with a lagged stock of innovations of zero (unreported).

robustness of our results controlling for the other major regulation against pollution, the National Emission Ceilings Directive (NECD) (see section 2.2). More precisely, we estimate our model on regions of countries that never exceeded their national emission ceilings for NOx over the period post-2010, when the NECD entered into force.[14] This represents 14 countries (out of 28) that should not have implemented any further actions or programmes to reach NECD targets. Estimation results on this sub-sample (column 2 of Table 4) give very similar conclusions.

We also check the robustness of our results with respect to infrigement cases. As stated before, the AAQD is a relatively effective regulation and most countries and regions do implement environmental measures in case of exceedances. Indirect evidence that the regulation is enforced succesfully is that air pollution concentration declines more rapidely in exceeding regions than in non-exceeding regions (see Figure 2). However, one can still argue that some Member States still fail to comply because the regulation is not implemented forcefully in all regions. Indeed, the European Commission (EC) currently purusues infringement proceedings at various stages on NO2 and PM10 against several Member States and referred eight countries to the European Court of Justice (ECJ) (second to last stage of the procedure). This means that the EC and/or the ECJ considers that these countries did not implement sufficient and appropriate measures to reduce pollution. Therefore, as a robustness check, we redo the estimation on a sub-sample excluding these eight countries that have been referred to the ECJ for not complying with the AAQD (Bulgaria, Poland, Hungary, Italy, Romania, France, Germany and the United Kingdom). Estimations on this sub-sample reported in column 3 show broadly similar results. Regulated regions seem to innovate more in CCMTs in clean energy (Y02E) (as compared to non-CCMTs) but less in CCMTs in waste and wastewater (Y02W). Intestingly, the negative coefficient for CCMTs in energy intensive industries becomes insignificant

[14] The NECD also concerns three other pollutants that we do not consider here, i.e. non-methane volatile organic compounds (NMVOCs), sulphur dioxide (SO2), ammonia (NH3) and a fourth pollutant, fine particulate matter (PM2.5) after 2016.

in this case.

Last but not least, we control for the existence of potential omitted variables by introducing additional variables in the regression. In columns (4), (5) and (6) of Table 4, we include as additional control variables the annual mean concentration of pollution in PM10, NO2 and O3 per region and year interacted with the dummy variables identifying CCMTs.[15] This allows us to test whether our variable measuring exceedances of limit values is a good proxy for changes in environmental regulation and does not capture only the level of pollutants concentration. We still find that our interaction variable for environmental regulation remains positive and significant for clean energy and smart grids to some extent, and negative for CCMTs in energy intensive industries and waste and wastewater to some extent.

3.3 Dynamic and spatial analysis

In order to investigate further the specialisation of regions in CCMTs, we introduce some dynamic and spatial analysis. We first examine whether the environmental regulation affects innovation specialisation immediately or with delays. We then analyse the geographical extent of the regulation's impact.

Dynamic analysis Innovations might react with delays. To analyse the impact of the environmental regulation overtime, we estimate our model introducing contemporary but also lagged measures of the regulation. Estimation results when using the dummy for the regulation variable are reported in Table 5.[16] Column (1) displays the contemporary effect of the regulation, while columns (2) and (3) report

[15]Note that, in this specification, the level of pollutants concentration is captured by region-year fixed effects. For this reason, in this Table, we only add the interaction between the level of emissions and the CCMT dummy variables.

[16]To save space, we do not report here the results obtained with the dummy variable computed specifically for each pollutant (PM10, NO2 and O3), nor the results using the intensive variables (share of exceeding stations and average exceedance levels above the limit value). Results are available upon request.

the effects of the regulation on specialisation in CCMTs after respectively 1 year and 2 years. There seems to be both contemporary effects of the regulation and effects after 2 years. After 2 years, we find that the regulation affects all sub-classes related to CCMTs except CCMTs in builidings (Y02B). A positive coefficient is found for Capture (Y02C), Energy (Y02E) and Smart grids (Y04S) and a negative one is found for Industry and agriculture (Y02P), Transport (Y02T) and Waste and wastewater (Y02W). When comparing contemporary effects and effects after 1 or 2 years for each sub-class, note that all signs remain the same in the three cases for coefficients that are statistically significant. Therefore, it seems that the effects of the regulation are rather stable overtime.

Spatial analysis Innovations might also be global and not local. In order to investigate further the geographical pattern of innovations, we first redo the estimation at the country (instead of the regional) level. Our dependent variable in this case is the count of patents for a given country, technological class and year ($Patents_{ict}$) and our variable of interest is an interaction between the dummy that takes the value one in case of exceedance of the limit value in country i and year t and the dummy to identify CCMTs.

Country-level estimation might offer three main advantages. First, most environmental measures to comply with the Air Quality Directive are defined at the local or regional levels but some of them are defined or implemented on a wider basis. Second, it is countries and not regions that are responsible for the implementation of environmental measures and when the European Commission considers that the regulation is not enforced, it launches legal proceedings agianst countries. Therefore, the main constraint imposed by the regulation could be perceived at the country level. Finally, estimations at the regional level may underestimate the effect of the regulation because regions that are constrained by the regulation are not necessarily regions where inventors are located (as the innovations are assigned to regions

Table 5: Environmental regulation (dummy for Any Pollutant) and CCMTs at the region level with lagged effects

	Contemporary $RegAQ_{rt}$ (1)	Lag (1 year) $RegAQ_{rt-1}$ (2)	Lag (2 years) $RegAQ_{rt-2}$ (3)
$RegAQ$×YBuilding	0.0239	-0.0317	-0.00692
	(0.0472)	(0.0525)	(0.0484)
$RegAQ$×YCapture	.0407	0.0857	0.260***
	(0.0967)	(0.105)	(0.0985)
$RegAQ$×YEnergy	0.126***	0.0312	0.145***
	(0.0296)	(0.0329)	(0.0291)
$RegAQ$×YProd	-0.106***	-0.0391	-0.120***
	(0.0326)	(0.0357)	(0.0316)
$RegAQ$×YTransport	-0.0238	0.0351	-0.119***
	(0.0361)	(0.0411)	(0.0361)
$RegAQ$×YWaste	-0.121**	-0.184***	-0.198***
	(0.0557)	(0.0661)	(0.0576)
$RegAQ$×YSmartGr	0.0979	0.109	0.348***
	(0.0972)	(0.109)	(0.0990)
$\ln Patents\ Stock_{rct-1}$		0.0982***	
		(0.0113)	
Observations		1,053,091	
Region-class FE		yes	
Region-year FE		yes	
Class-year FE		yes	

Notes: The dependent variable is the weighted counts of patents per EU region and year. Robust standard errors clustered at the region-year in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. The regression includes a dummy variable to account for observations with a lagged stock of innovations of zero (unreported).

through the region of residence of inventor). On the other hand, estimation at the country level leads to a less reliable identification of the effect of the regulation.

Country-level estimates are reported in Table 6. They are generally consistent with regional level estimates. They tend to indicate that countries implementing environmental measures in order to comply with the EU regulation do not generally tend to innovate more in CCMTs (columns 1, 3, 5 and 7 of Table 6). However, when we disaggregate CCMTs into different sub-classes (columns 2, 4, 6 and 8) we obtain differential impacts on different technology fields. Countries that implement additional environmental measures tend to innovate more in energy sources alternative to fossil fuels (Y02E) and in smart grids (Y04S) (as compared to non-CCMTs). But, they innovate less in CCMTs in energy intensive industries (Y02P), in waste and wastewater (Y02W) and in transportation (Y02T) to some extent.

We also introduce regional spatial dynamics with an additional variable evaluating the regulation of the other regions (q) in the country weighted by the distance between each innovative region and the regulated regions. More precisely, we estimate the following equation:

$$\begin{aligned} Patents_{rct} &= exp(\beta_1(1-\delta)K_{rct-1} + \beta_2 RegAQ_{rt} \times CCMT_c \\ &+ \beta_3 \frac{\sum_{q\neq r} RegAQ_{qt} \times (1/Dist_{qr})}{\sum_{l\neq r}(1/Dist_{qr})} \times CCMT_c + \alpha_{rc} + \alpha_{c1t} + \alpha_{rt}) + \epsilon_{rct} \end{aligned} \quad (2)$$

In this equation, β_3 measures the specialisation in CCMTs of each innovative region when other regions in the country implement additional environmental measures. The corresponding variable takes values between 0 and 1. It is 0 (resp. 1) when no other (resp. all other) regions of the country exceed the limit value in a given year. Its value is closer to 1 when close regions exceed as compared to more distant regions.

Estimation results are displayed in Table 7. The positive effect of the regulation on

Table 6: Environmental regulation (dummy) and CCMTs at the country level

	Any Pollutant		PM10d		NO2h		O3	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$RegAQ_{it}\times Y$	-0.0496		-0.0669**		0.00719		-0.0497*	
	(0.0399)		(0.0268)		(0.0323)		(0.0271)	
$RegAQ_{it}\times$YBuilding		-0.0422		-0.0443		-0.00752		-0.0841**
		(0.0548)		(0.0454)		(0.0454)		(0.0394)
$RegAQ_{it}\times$YCapture		0.114		0.135		0.0330		0.0379
		(0.103)		(0.0945)		(0.0778)		(0.0849)
$RegAQ_{it}\times$YEnergy		0.147***		0.118***		0.0865		0.0359
		(0.0479)		(0.0378)		(0.0548)		(0.0528)
$RegAQ_{it}\times$YProd		-0.266***		-0.257***		-0.0941*		-0.136**
		(0.0584)		(0.0499)		(0.0554)		(0.0537)
$RegAQ_{it}\times$YTransport		-0.173***		-0.202***		-0.0165		-0.0780*
		(0.0495)		(0.0377)		(0.0438)		(0.0404)
$RegAQ_{it}\times$YWaste		-0.298***		-0.284***		-0.0627		-0.135**
		(0.0627)		(0.0544)		(0.0660)		(0.0654)
$RegAQ_{it}\times$YSmartGr		0.318***		0.255***		0.362***		0.314***
		(0.0878)		(0.0883)		(0.0969)		(0.0994)
$\ln Patents\ Stock_{ict-1}$	0.515***	0.515***	0.515***	0.512***	0.515***	0.513***	0.515***	0.513***
	(0.0271)	(0.0271)	(0.0271)	(0.0269)	(0.0271)	(0.0270)	(0.0271)	(0.0271)
Observations	196,440	196,440	196,440	196,440	196,440	196,440	196,440	196,440
Country-class FE	yes	yes	yes	yes	yes	yes	yes	yes
Country-year FE	yes	yes	yes	yes	yes	yes	yes	yes
Class-year FE	yes	yes	yes	yes	yes	yes	yes	yes

Notes: The dependent variable is the weighted counts of patents per EU country and year. Robust standard errors clustered at the country-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1. The regression includes a dummy variable to account for observations with a lagged stock of innovations of zero (unreported).

CCMTs in clean energy (Y02E) are found both in the regulated region and in other (unregulated) regions close to the regulated ones (columns 1, 3 and 4). However, for CCMTs in industry and agriculture (Y02P), in waste and wastewater (Y02W) and in transportation to some extent (Y02T) the negative impact is mainly found in other (unregulated) regions that are close to the regulated ones. In these cases, the coefficient on $RegAQ_{rt}$ is not significant, while the coefficient on $RegAQ_{-rt}$ is negative and significant. Note that when we introduce a similar variable for the regulation in other regions ($RegAQ_{-rt}$) not weighted by the distance, we obtain very similar results (available upon request).

4 Results discussion and conclusion

Our preliminary results display how environmental stringency translates into changes in patterns of innovation at the region and country levels. More specifically, our results depict non-homogenous reactions but thus also pinpoint several areas for further investigation.

To develop the interpretation of the diverging impacts of environmental regulation in different technology fields we plan to refine our analysis in two ways. First, these diverging effects might be driven by a subset of countries because countries can be highly specialized in some technology classes. We thus intend to disentangle our estimations over different sub-samples to test whether our main conclusions do not depend on a specific country or technology class. Second, we will also identify the technologies that are used in sectors that are the most affected by the regulation (pollution intensive sectors) in order to take into account and control for the effect of the regulation on the activity. We want to test whether the diverging effects of regulation on innovations can be explained by the shrink of some economic sectors which activity should fall under the environmental regulation. To take an example,

Table 7: Environmental regulation (dummy) and CCMTs at the regional level with spatial anaysis

	Any Pollutant (1)		PM10d (2)		NO2h (3)		O3 (4)	
	Region reg ($RegAQ_{rt}$)	Rest of cty reg ($RegAQ_{-rt}$)	Region reg ($RegAQ_{rt}$)	Rest of cty reg ($RegAQ_{-rt}$)	Region reg ($RegAQ_{rt}$)	Rest of cty reg ($RegAQ_{-rt}$)	Region reg ($RegAQ_{rt}$)	Rest of cty reg ($RegAQ_{-rt}$)
$RegAQ_{rt}$ or $RegAQ_{-rt}$								
×YBuilding	-0.0390	0.000678	0.0136	0.00450	0.00727	0.228	0.0404	-0.160
	(0.0482)	(0.0783)	(0.0492)	(0.0843)	(0.0720)	(0.264)	(0.0812)	(0.114)
×YCapture	-0.0295	0.208	-0.0910	0.173	0.370**	-0.377	0.256	-0.121
	(0.119)	(0.192)	(0.109)	(0.218)	(0.149)	(0.697)	(0.173)	(0.241)
×YEnergy	0.0919***	0.234***	0.141***	0.0783	0.207***	1.172***	0.113**	0.122*
	(0.0353)	(0.0611)	(0.0338)	(0.0676)	(0.0426)	(0.186)	(0.0495)	(0.0729)
×YProd	-0.0497	-0.468***	-0.0155	-0.513***	0.0157	-1.388***	-0.0514	-0.350***
	(0.0385)	(0.0658)	(0.0373)	(0.0758)	(0.0444)	(0.246)	(0.0525)	(0.0802)
×YTransport	0.0293	-0.230***	-0.0164	-0.187**	-0.0515	0.266	-0.00634	-0.107
	(0.0422)	(0.0735)	(0.0408)	(0.0842)	(0.0448)	(0.225)	(0.0577)	(0.0915)
×YWaste	-0.109*	-0.565***	-0.0905	-0.581***	0.0229	-1.385***	0.108	-0.620***
	(0.0633)	(0.108)	(0.0647)	(0.119)	(0.0946)	(0.432)	(0.0952)	(0.134)
×YSmartGr	0.0485	0.344*	0.0901	-0.0576	0.428***	2.658***	0.0196	0.574**
	(0.107)	(0.190)	(0.105)	(0.197)	(0.131)	(0.496)	(0.150)	(0.229)
$\ln Patents\ Stock_{rct-1}$	0.152***		0.153***		0.153***		0.153***	
	(0.00977)		(0.00977)		(0.00977)		(0.00978)	
Region-class (rc) FE	Yes		Yes		Yes		Yes	
Class-year (c_1t) FE	Yes		Yes		Yes		Yes	
Region-year (rt) FE	Yes		Yes		Yes		Yes	
Observations	1,214,456		1,214,456		1,214,456		1,214,456	

Notes: The dependent variable is the weighted counts of patents per EU region and year. Robust standard errors clustered at the region-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1. The regression includes a dummy variable to account for observations with a lagged stock of innovations of zero (unreported).

imagine an environmental regulation that shrinks the activity of the manufacture of basic iron and steel (NACE code 2410). We expect this should also decrease the incentive to innovate in technologies related to process efficiency in electric arc furnaces (CPC code Y02P 10/259), as these technologies are mainly used by the steel industry.

We also intend to extend our research using a new piece of information in the data. In our initial database we did not have the information on the destination country where the applicants wish to protect their invention (because as for now we have only used information on the country of residence of the inventor). But we plan to extract and use this additional information in order to compare the results with the negative local impact of environmental regulation on CCMT inventions in specific countries and technology fields.

We will also exploit the differences between pollutants because each pollutant has specific sources (for instance road traffic for NO2), and therefore requires a certain set of environmental measures, that may affect more extensively some technology classes.

Concerning more specifically the regional setting, we will introduce spatial dynamics to test whether the regions that are constrained by the regulation are the ones where innovations take place and whether other regions (in a given country) also react to the regulation. In particular, we plan to include in the region-level estimations, variables capturing the distance of regulated regions to the stock of knowledge of other regions, the distance of innovative regions to regulated regions and the rest of the country regulation change.

Finally, despite our effort to limit endogeneity issues using a wide range of region-year fixed effects, our results could still be affected by endogeneity. Polluting industry lobbying in strategic domestic sectors may influence the type of measures chosen by national authorities to meet the limit values, preventing the implementation of measures constraining polluting industrial activity. To overcome this endogeneity bias, we will also implement an instrumental variable (IV) methodology, based on Broner et al. (2012) and Bagayev and Lochard (2017). To instrument environmental regulation, we will compute for every EU region and year a ventilation coefficient measuring the speed at which pollutants disperse in the air. The ventilation coefficient is based on two meteorological processes: wind and the depth of the atmospheric mixed layer which contribute largely to the dispersion of air pollution in the atmosphere. This instrument satisfies the two conditions for a good instrument: it is relevant for explaining exceedances of the AQFD limit values and it is uncorrelated with the error term.

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Appendix A: Data

Table 8: Data description and sources

Variables	Description and sources
$Patents_{rct}$	Count of patent applications to the EPO in a technological class c, in a NUTS-2 region r of the EU28 country (region of residence of the inventor) and a year t (date of priority). To avoid double counting, applications are divided equally among the regions of the inventors and CPC codes (fractional counting, see text for details). Source: EPO Worldwide Patent Statistical Database (PATSTAT).
$\ln PatentsStocks_{rct-1}$	Stock of patents of region r in technological class c at time $t-1$ (in logarithm). The stock variable is constructed using the perpetual inventory method with knowledge depreciation rate set at 20% and the value of a given patent set to zero after 20 years.
Y, $YBuilding$, $YCapture$...	Cooperative Patent Classification (CPC) sections corresponding to Climate Change Mitigation Technologies (CCMTs) based on the tagging scheme developped by the EPO (Y02/Y04S). This section is decomposed into 7 sub-classes (Y02B, Y02C, Y02E, Y02P, Y02T, Y02W, Y04S) (see Table 10 below).
$RegAQ_{rt}$	Environmental regulation proxy. This variable is a dummy that takes the value 1 if emission concentration for NO2, PM10, O3 or any of the three exceed the limit value (more than the number of exceedances allowed each year) in at least one of the stations located in region r (see Table 9). As alternative proxies, we use a variable that measures the share of stations in exceedance in each region and year (Sh. Stations) and the level of exceedances (Exc. Level) i.e. average number of days or times of exceedance by region and year over the allowed level. Exceedance data come from the AirBase database (European Environment Agency, EEA).
$\ln MeanPol$	Annual mean concentration of pollution in PM10, NO2 and O3 per region and year. Data come from the AirBase database (European Environment Agency, EEA).
PIT_c	

Appendix B: Additional results

Table 9: Pollutant limit values as given by the EU Ambient Air Quality Directive

Pollutant	Concentration	Averaging period	Limit value enters into force	Allowed exceedances each year
Sulphur dioxide (SO2)	350 μg/m3	1 hour	1.1.2005	24
	125 μg/m3	24 hours	1.1.2005	3
Nitrogen dioxide (NO2)	200 μg/m3	1 hour	1.1.2010	18
	40 μg/m3	1 year	1.1.2010	None
PM10	50 μg/m3	24 hours	1.1.2005	35
	40 μg/m3	1 year	1.1.2005	None
Lead (Pb)	0.5 μg/m3	1 year	1.1.2005 (or 1.1.2010 in specific cases)	n/a
Carbon monoxide (CO)	10 mg/m3	Max daily 8-h mean	1.1.2005	n/a
Benzene (C6H6)	5 μg/m3	1 year	1.1.2010	n/a
Ozone (O3)	120 μg/m3	Max daily 8-h mean	1.1.2010 (T.V.)	25
PM2.5	25 μg/m3	1 year	1.1.2015 (T.V. 1.1.2010)	

Notes: Lead limit value enters into force in 1.1.2010 in the immediate vicinity of some specific industrial sources. For ozone, target value instead of limit value. For PM2.5, target value 1.1.2010 and limit value after 1.12015. The first Daughter Directive (1999/30/EC) introduces limit values for SO2, NO2, PM10 and Pb. The second Daughter Directive (2000/69/EC) introduces limit values for CO and C6H6. The third Daughter Directive (2002/3/EC) establishes target values for O3. The AAQD completes the list of pollutants and imposes a limit value for PM2.5.

Table 10: Climate Change Mitigation Technologies (CCMTs) in the Y02/Y04S scheme

CPC group	Name	Description and Examples
Y02B	Buildings	Use of renewables energy sources in buildings, energy efficient lighting, heating, etc.
Y02C	Capture and storage of greenhouse gases	Capture by biological separation, chemical separation, etc.
Y02E	Production, distribution and transport of energy	Energy sources alternative to fossil fuels (e.g. renewable), efficient transmission and distribution technologies
Y02P	Industry and agriculture	CCMT in energy intensive industries (chemical, agriculture, agroindustry, etc.)
Y02T	Transportation	Technologies for making transportation less carbon-intensive (e.g. electric vehicles)
Y02W	Waste and wastewater	Technologies related to waste-water treatment (e.g. biological treatment of water) and solid waste (e.g. recycling and recovery)
Y04S	Smart grids	Remote control of power generators, interoperability of electric and hybrid vehicles, energy trading, etc.

Notes: The Y02 scheme now includes two additional categories Y02A (Adaptation to climate change) and Y02D (ICT aiming at the reduction of own energy use). A majority of Y04S also relate to CCMT. Therefore, patents tagged with the Y04S code are often also coded under other Y02 categories.

Table 11: Environmental regulation (dummy) and CCMTs on individual countries

	Any Pollutant France (1)	Any Pollutant Germany (2)	Any Pollutant Italy (3)	Any Pollutant Spain (4)	Any Pollutant UK (5)
RegAQ*YBuilding	-0.166	-0.00671	0.196	0.194	-0.309
	(0.141)	(0.0556)	(0.191)	(0.284)	(0.194)
RegAQ*YCapture	-0.0849	0.262*	-0.0344	0.0981	-0.741
	(0.170)	(0.141)	(0.335)	(0.514)	(0.520)
RegAQ*YEnergy	0.345***	0.183***	0.327*	0.665***	0.164
	(0.0736)	(0.0410)	(0.187)	(0.198)	(0.170)
RegAQ*YProd	-0.298***	-0.202***	-0.527***	-0.622***	-0.463**
	(0.0775)	(0.0421)	(0.193)	(0.198)	(0.195)
RegAQ*YTransport	-0.0979	-0.0213	-0.231	-0.193	-0.252
	(0.0867)	(0.0424)	(0.191)	(0.301)	(0.246)
RegAQ*YWaste	-0.255***	-0.324***	-0.369*	-0.270	-0.900**
	(0.0930)	(0.0680)	(0.207)	(0.269)	(0.384)
RegAQ*YSmartGr	0.499**	0.181*	-0.0157	-0.508	0.839**
	(0.211)	(0.101)	(0.304)	(0.547)	(0.348)
$\ln Patentstock_{rct-1}$	0.158***	0.233***	0.0417*	0.0497	0.0729***
	(0.0251)	(0.0159)	(0.0242)	(0.0313)	(0.0178)
Observations	154,391	333,143	112,956	54,615	231,681
Region-class FE	yes	yes	yes	yes	yes
Region-year FE	yes	yes	yes	yes	yes
Class-year FE	yes	yes	yes	yes	yes

Notes: The dependent variable is the weighted counts of patents per EU country and year. Robust standard errors clustered at the region-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1. The regression includes a dummy variable to account for observations with a lagged stock of innovations of zero (unreported).

Table 12: Environmental regulation (dummy) and CCMTs excluding each CPC class

Excluding:	Any Pollutant CPC class A (1)	Any Pollutant CPC class B (2)	Any Pollutant CPC class C (3)	Any Pollutant CPC class D (4)	Any Pollutant CPC class E (5)	Any Pollutant CPC class F (6)	Any Pollutant CPC class G (7)	Any Pollutan CPC class (8)
RegAQ*YBuilding	-0.00198	-0.00793	0.000265	-0.000737	-0.00650	-0.0149	-0.00343	-0.0036
	(0.0386)	(0.0382)	(0.0383)	(0.0386)	(0.0385)	(0.0387)	(0.0387)	(0.0394
RegAQ*YCapture	0.0819	0.0697	0.0862	0.0821	0.0788	0.0734	0.0897	0.0858
	(0.0900)	(0.0890)	(0.0898)	(0.0897)	(0.0895)	(0.0901)	(0.0896)	(0.0906
RegAQ*YEnergy	0.216***	0.203***	0.219***	0.215***	0.209***	0.202***	0.220***	0.228**
	(0.0291)	(0.0290)	(0.0293)	(0.0293)	(0.0293)	(0.0300)	(0.0292)	(0.0297
RegAQ*YProd	-0.219***	-0.225***	-0.218***	-0.220***	-0.221***	-0.229***	-0.216***	-0.227**
	(0.0320)	(0.0327)	(0.0327)	(0.0323)	(0.0323)	(0.0328)	(0.0324)	(0.0322
RegAQ*YTransport	-0.0315	-0.0352	-0.0295	-0.0332	-0.0356	-0.0484	-0.0278	-0.0283
	(0.0324)	(0.0337)	(0.0328)	(0.0330)	(0.0330)	(0.0344)	(0.0331)	(0.0324
RegAQ*YWaste	-0.351***	-0.349***	-0.344***	-0.349***	-0.349***	-0.358***	-0.342***	-0.366**
	(0.0455)	(0.0459)	(0.0458)	(0.0457)	(0.0456)	(0.0459)	(0.0457)	(0.0457
RegAQ*YSmartGr	0.217***	0.212***	0.220***	0.219***	0.215***	0.201**	0.223***	0.227**
	(0.0791)	(0.0797)	(0.0794)	(0.0791)	(0.0792)	(0.0795)	(0.0795)	(0.0792
$\ln Patentstock_{rct-1}$	0.157***	0.171***	0.156***	0.153***	0.163***	0.156***	0.154***	0.112**
	(0.00929)	(0.0106)	(0.0104)	(0.00991)	(0.00994)	(0.0102)	(0.00946)	(0.00905
Observations	1,049,599	923,654	1,048,226	1,173,610	1,144,314	1,029,849	1,075,191	1,102,33
Region-class FE	yes	yes	yes	Yes	yes	yes	yes	yes
Region-year FE	yes	yes	yes	Yes	yes	yes	yes	yes
Class-year FE	yes	yes	yes	Yes	yes	yes	yes	yes

Notes: The dependent variable is the weighted counts of patents per EU country and year. Robust standard errors clustered at the region-year in parentheses. p<0.01, ** p<0.05, * p<0.1. The regression includes a dummy variable to account for observations with a lagged stock of innovations of zero (unreported).