Innovation in climate change mitigation technologies and environmental regulation

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Innovation and Climate Change Governance Conference

INRAE 19-20 May, 2022

Outline

1.1 Motivation

- Air pollution regulations are widely implemented (124 out of 195 countries, UNEP, 2021)
- All the more necessary given human health impact
- But also because air pollution and climate change are closely interlinked (EEA, 2016)
- The ability of air pollution regulations to temper climate change and its associated costs largely depends on their impact on technological change

1.1 Motivation

- Environmental regulations, by imposing limits on polluting emissions or by increasing their costs, modify the relative costs and benefits of competing technologies (Acemoglu et al., 2012)
- But, redirecting technological change is not straightforward
  - Path dependence (Aghion et al., 2016)
  - Environmental regulation in one country could divert polluting activities toward less regulated countries (pollution havens)

1.1 Motivation and research question

- Do air pollution regulations stimulate innovations that mitigate climate change?
- In this paper we focus on the EU Ambient Air Quality Directive (AAQD): major but understudied policy

  ⇒ We investigate the impact of EU AAQD on specialisation of European regions in green technologies

1.2 Brief literature review

- Large literature on directed technological change and the environment
- Positive relationship between environmental regulation and innovations (Lanjouw and Mody, 1996; Popp, 2010)
  - Macro-evidence (Hascic, Johnstone and Michel, 2012; Johnstone, Hascic and Popp, 2010)
  - Micro-evidence (Aghion et al., 2016; Calel and Dechezleprêtre, 2016)
- Major empirical challenges in identifying causal impact:
  - Multidimensions of environmental regulation
  - Simultaneity
  - Unobserved heterogeneity

1.3 Main contributions and research design

- Original variable that evaluates changes in environmental regulation stringency based on the principles of the EU AAQD
  - Sets numerical limits for different pollutants and requires regions to implement policy and measures
- Regional setting
  - Most programs implemented at the regional level
  - Innovation activity localized
- Empirical strategy to control for unobserved heterogeneity and avoid simultaneity including a wide range of fixed effects and an Instrumental Variable (IV)

2 Empirical strategy

Poisson specification for patents determinants and quasi difference-in-difference setting:

$$\begin{aligned} Patents_{rct} &= exp(\beta_1(1-\delta)K_{rct-1} + \beta_2 RegAQ_{rt} \times Green_c \\ &+ \beta_3 RegAQ_{rt} \times GRelated_c + \alpha_{rc} + \alpha_{c1t} + \alpha_{rt}) + \varepsilon_{rct} \quad (1) \end{aligned}$$

- $Patents_{rct}$ are patents of region r in tech. class c at time t, and K_{rct-1} is the stock of patents in the previous year. Depreciation of knowledge stock δ set at 20%
- $RegAQ_{rt}$ is our measure of environmental regulation change in region r at time t and $Green_c$ is a dummy for green technology classes ; $GRelated_c$ is a dummy for green related technology classes Detail
- Range of region-year, region-class and class-year (1 digit or 4 digits) fixed effects

3 Sample and data

Sample:

- 273 regions (NUTS 2) in 28 EU countries
- Time period: 1999-2015

Main data:

- Patents data (applications): EPO Patstat
  - Use information on the region of residence of the inventor
  - 652 technological classes (4 digits)
  - Fractional counting
- Environmental regulations: based on data from European Environmental Agency (EEA)

3.1 Green innovations

- To identify green patents we use the new CPC that covers Climate Change Mitigation Technologies (CCMT) (Veefkind et al., 2012)

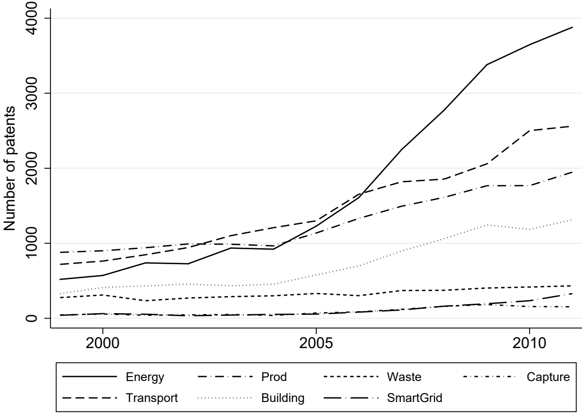
CPC group	Name	Description and Examples
Y02B	Building	Use of renewables energy sources in buildings, energy efficient lighting, heating, etc.
Y02C	Capture	Capture and storage of greenhouse gases - Capture by biological separation, chemical separation, etc.
Y02E	Energy	Production, distribution and transport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

3.1 Evolution of green innovations

- Green patents have grown extensively over the last decades
  - The amount of patents published worldwide in 'clean energy' has been multiplied by 4 between 1995 and 2008, whereas the total amount of patents has only doubled (Veefkind et al., 2012)
  - The average share of green innovations in the total number of patents is now approx 5% in the EU
  - There is also a substantial heterogeneity in the share of green innovations among EU regions

3.1 Evolution of green innovations

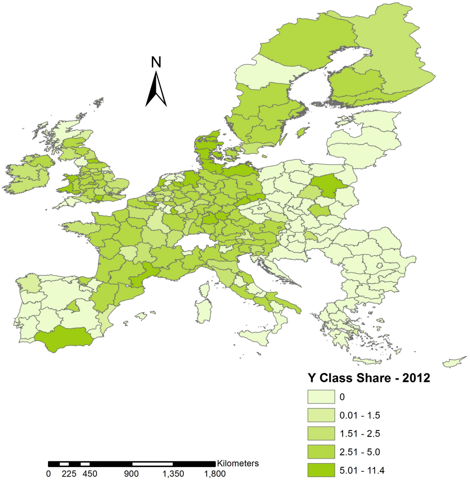
Figure: Evolution of the number of green patents over the period 1999-2011



Source: PATSTAT.

3.1 Regional specialisation in green technologies

Figure: Average share of green patents in the total number of patents by EU region in 2012



Source: PATSTAT.

3.2 EU regulation on air quality (RegAQ)

We exploit the main regulatory tools to fight air pollution in the EU: Ambient Air Quality Directive (AAQD)

- Set numerical limits for different types of air pollutant concentration (SO2, NOx, PM, O3, etc.) table
- Require EU regions/countries to implement environmental measures (short-term and long-term) in case of exceedance
  - Ex: prescription to use high pollutant fuels in industry, development and adoption of clean technologies, traffic restrictions, etc.
  - Mostly at the regional level (89% of all measures since 2012), the rest (11%) being at the country level

3.2 EU regulation on air quality (RegAQ)

- We focus on PM10 and NO2 : represent the target of 68% of all air quality plans since 2004
- Proxy for environmental measures ($RegAQ_{rt}$): exceedance of limit values (0/1 variable) for each pollutant (PM10 and NO2), region and year
- We use a complementary measure of the 'intensity' of the regulation:
  - The average number of days/times of exceedance above the limit value over the allowed level for each pollutant and year

3.2 EU regulation on air quality (RegAQ)

Main advantages:

- Regions might implement any policy or measure in case of exceedance $\Rightarrow$ Accounts for the multidimensions of environmental regulation
- Limit values are the same for all MS and are defined to protect human health (WHO guidelines) $\Rightarrow$ Partially solves the simultaneity problem
- Limits are legally binding $\Rightarrow$ Plans and measures are regularly evaluated and the AAQD is the most constraining legislation

First introduced by Bagayev and Lochard (2017). Similar approach to proxy changeS in regulation in the U.S. (Clean Air Act) (Becker and Henderson, 2000; Hanna, 2011)

3.3 Main mechanisms

- Firms might *directly* respond to the regulation by developing innovations that allow them to comply with air quality standard or to reduce the cost of the regulation
- Possible *indirect* effect if higher adoption of green innovations in regulated zones creates a demand-pull for green technologies and therefore fosters green innovation
- Illustrating example: Paris has installed carbon sinks to capture CO2 and NO2 thanks to the natural properties of microalgae
  $\hookrightarrow$ Corresponding patent filed by a French firm (Fermentalg) in May 2009 (B01D53/84; ... ; Y02A50/2358; Y02C10/02; Y02P20/59)

4.1 Main results

Table I: Environmental regulation and green innovations
Dependent variable: Weighted count of patents
Method: Poisson

	PM10		NO2	
	(1)	(2)	(3)	(4)
$RegAQ_{rt} \times Green_c$	**0.0323***		**0.0513****	
	(0.0183)		(0.0250)	
$RegAQ_{rt} \times \text{Building}_c$		**0.115*****		0.0774
		(0.0434)		(0.0577)
$RegAQ_{rt} \times \text{Capture}_c$		-0.0850		0.212
		(0.101)		(0.152)
$RegAQ_{rt} \times \text{Energy}_c$		**0.0792*****		**0.127*****
		(0.0296)		(0.0387)
$RegAQ_{rt} \times \text{Prod}_c$		**0.0598****		**0.120*****
		(0.0296)		(0.0453)
$RegAQ_{rt} \times \text{Transport}_c$		0.0251		0.0479
		(0.0377)		(0.0561)
$RegAQ_{rt} \times \text{Waste}_c$		0.0786		**0.143***
		(0.0556)		(0.0828)
$RegAQ_{rt} \times \text{SmartGr}_c$		0.0262		0.159
		(0.0933)		(0.141)
$\ln Patents\ Stock_{rct-1}$	0.216***	0.215***	0.211***	0.210***
	(0.0115)	(0.0114)	(0.0115)	(0.0113)
Control: RegAQ $\times$ *GRelated*	Yes	Yes	Yes	Yes
Region-class (rc) FE	Yes	Yes	Yes	Yes
Class-year ($c_1 t$ and $c_4 t$) FE	Yes	Yes	Yes	Yes
Region-year (rt) FE	Yes	Yes	Yes	Yes
Observations	1,198,944	1,198,944	1,198,944	1,198,944

4.1 Main results

- Positive effects of the AAQD on specialisation of EU regions in green innovations in *Energy* and in the *Production or processing of goods*
  - *Energy*: increase of 8.2% (PM10 measures) and 13.5% (NO2)
  - *Prod*: increase of 6.2% (PM10 measures) and 12.7% (NO2)
  - Cumulative effect after 10 years: 12%-26%
- No effect on green innovations in transportation
- Some positive effect on green innovations in buildings (PM10 measures) and in waste and wastewater (NO2 measures)

4.2 Results: Robustness

- Results robust with respect to:
  - Our regulation proxy (sub-samples) and control of pollution levels table
  - Alternative regulation variable (exceedance levels instead of the dummy)
  - A placebo test using a kind of discontinuity design: we define 'placebo-treated' regions using threshold values of pollution concentrations that are close but lower than official levels
  - The introduction of lags (delayed effect of the regulation on innovation) figure
  - The introduction of regional (NUTS-2) spatial dynamics

4.3 Results: Spatial dynamics

Innovations might not be local:

- Environmental measures implemented in one region could induce more green patents in other (close) regions
- Conversely, innovators might engage in more green innovations in regulated regions but less so in neighbouring unregulated regions (spatial leakage)

We introduce spatial dynamics: regulation of the other regions in the country weighted by the distance

⇒ Positive impact of the AAQD on green innovations in energy and in the production or processing of goods mainly local

⇒ Some evidence of spatial leakage table

4.4 Endogeneity

Despite fixed effects and a diff-in-diff framework, still potential endogeneity concern

- Due to the latitude granted to countries in choosing measures to be implemented in case of exceedance

We implement a control function approach. Our instrument is the minimum monthly ventilation coefficient facing by any monitoring station in a given EU region each year

- We compute ventilation coefficients (wind*mixed layer) for a grid of 0.25 x 0.25 cells and merge these with geographical coordinates of monitoring stations

⇒ Our main conclusion remains: positive impact of the AAQD on regional specialisation in green innovations table

5 Conclusion and way forward

- We find a positive effect of the AAQD on specialisation in green innovations in general and differential impacts :
  - Regulated regions tend to specialise more in clean energy and in green innovations in the production or processing of goods
  - We do not find any effect on green innovations in transportation
- Avenues for further research:
  - Compare the effects of different policy instruments
  - Identify the degree to which technologies are 'environmentally friendly'
  - Account for the cost of innovation in different technology fields

That's all folks!

Thank you

[Supplementary] 2 Empirical model - Green related technologies

- We account for the interrelations between green and other classes using additional dummy variables interacted with RegAQ variables:

$$GRelated_c = \begin{cases} 1 & \text{if } \phi_{c'c} > 1 \\ 0 & \text{if } \phi_{c'c} \in [0;1] \end{cases} \quad (2)$$

where $\phi_{c'c}$ is the probabilistic co-occurence between each non-green class c' and a green class c. Back to main

[Supplementary] 3.2 EU regulation on air quality (RegAQ)

Table: Pollutant limit values from the Ambient Air Quality Directive (AAQD)

Pollutant	Concentration	Averaging period	Limit value enters into force	Allowed exceedances each year
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

Back to main.

[Supplementary] 4.2 Further Robustness

Table II: Environmental regulation and green innovations - Robustness

Dependent variable: Weighted count of patents

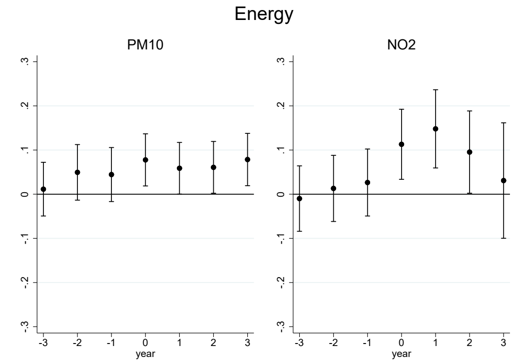
Method: Poisson

	w/o non-exceed reg.		No NECD	w/o infringement		with pollution control	
	PM10	NO2	NO2	PM10	NO2	PM10	NO2
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$RegAQ_{rt} \times \text{Building}_c$	0.140***	0.0920	0.0114	0.119***	0.178***	0.114***	0.0811
	(0.0473)	(0.0788)	(0.0747)	(0.0449)	(0.0675)	(0.0443)	(0.0583)
$RegAQ_{rt} \times \text{Capture}_c$	-0.0641	0.242	0.557***	-0.115	0.00581	-0.0481	0.212
	(0.103)	(0.217)	(0.206)	(0.102)	(0.187)	(0.108)	(0.157)
$RegAQ_{rt} \times \text{Energy}_c$	0.116***	0.259***	0.0851*	0.0860***	0.0719	0.0641**	0.121***
	(0.0318)	(0.0597)	(0.0496)	(0.0302)	(0.0503)	(0.0297)	(0.0385)
$RegAQ_{rt} \times \text{Prod}_c$	0.0769**	0.147***	0.234***	0.0707**	0.0972*	0.0608*	0.116**
	(0.0325)	(0.0659)	(0.0605)	(0.0313)	(0.0566)	(0.0325)	(0.0465)
$RegAQ_{rt} \times \text{Transport}_c$	0.0647	0.119	0.0465	0.0271	0.131*	0.0517	0.0591
	(0.0421)	(0.0771)	(0.0704)	(0.0386)	(0.0720)	(0.0394)	(0.0569)
$RegAQ_{rt} \times \text{Waste}_c$	0.107*	0.0189	0.130	0.0627	0.0668	0.0535	0.145*
	(0.0617)	(0.113)	(0.103)	(0.0581)	(0.0964)	(0.0600)	(0.0832)
$RegAQ_{rt} \times \text{SmartGr}_c$	0.0691	0.192	0.118	0.0569	0.0309	-0.0001	0.139
	(0.0980)	(0.214)	(0.198)	(0.0953)	(0.153)	(0.0992)	(0.140)
$\ln Patents\ Stock_{rct-1}$	0.245***	0.245***	0.203***	0.226***	0.142***	0.185***	0.210***
	(0.0134)	(0.0127)	(0.0120)	(0.0119)	(0.0155)	(0.0128)	(0.0116)
Pollution Level $\times$ $Green_c$	No	No	No	No	No	Yes	Yes
$RegAQ \times GRelated$	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region-class (rc) FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Class-year ($c_1 t$ and $c_4 t$) FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region-year (rt) FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	818,748	876,681	800,384	1,101,428	809,342	1,060,419	1,139,746

Back to main.

[Supplementary] 4.2 Lags and leads

Figure: The dynamic effect of the regulation on innovations in clean energy



Sources: Own estimation results. The vertical bars refer to the 95% confidence interval. The horizontal axis represents the number of years before and after exceedances of air quality limit values (PM10 or NO2)

Back to main

[Supplementary] 4.3 Results: Spatial dynamics

Table III: Regulation and innovation with control for regulation in other regions

Dependent variable: Weighted count of patents

Method: Poisson

	(1) PM10		(2) NO2	
	Region reg ($RegAQ_{rt}$)	Rest of the cty reg ($RegAQ_{-rt}$)	Region reg ($RegAQ_{rt}$)	Rest of the cty reg ($RegAQ_{-rt}$)
$RegAQ_{rt}$ or $RegAQ_{-rt}$				
$\times$Building$_c$	0.0642	0.281***	0.0805	-0.0681
	(0.0469)	(0.0992)	(0.0659)	(0.0960)
$\times$Capture$_c$	-0.126	0.261	0.0559	0.519**
	(0.104)	(0.265)	(0.163)	(0.235)
$\times$Energy$_c$	**0.0863*** **	**-0.201*** **	**0.107** **	0.0396
	(0.0305)	(0.0754)	(0.0455)	(0.0699)
$\times$Prod$_c$	**0.0672** **	**-0.158** **	**0.0981* **	0.0226
	(0.0325)	(0.0793)	(0.0547)	(0.0814)
$\times$Transport$_c$	0.0257	-0.192*	0.0474	-0.125
	(0.0392)	(0.105)	(0.0631)	(0.0998)
$\times$Waste$_c$	0.0684	0.0302	0.126	-0.0154
	(0.0612)	(0.136)	(0.0858)	(0.124)
$\times$SmartGr$_c$	0.0768	-0.729**	0.119	0.0526
	(0.0946)	(0.305)	(0.148)	(0.229)
ln $Patents\ Stock_{rct-1}$	0.216***		0.211***	
	(0.0114)		(0.0113)	
Control $RegAQ \times GRelated$	Yes		Yes	
Region-class (rc) FE	Yes		Yes	
Class-year (c_1t and c_4t) FE	Yes		Yes	
Region-year (rt) FE	Yes		Yes	
Observations	1,193,909		1,193,909	

Back to main.

[Supplementary] 4.4 Endogeneity - Control function

Table IV: Environmental regulation and green innovations - Control function

Dependent variable: Weighted count of patents

	PM10		NO2	
	Poisson	2SRI	Poisson	2SRI
	(1)	(2)	(3)	(4)
$RegAQ_{rt} \times \text{Green}_c$	0.0331**	0.476***	0.0502**	0.644***
	(0.0167)	(0.155)	(0.0248)	(0.198)
$\ln Patents\ Stock_{rct-1}$	0.822***	0.822***	0.822***	0.822***
	(0.00339)	(0.00339)	(0.00339)	(0.00339)
Control Function Residuals:				
$RegAQ_{rt} \times Green_c$ (residual)		-0.450***		-0.600***
		(0.158)		(0.200)
1st stage				
Dep. variable: $RegAQ_{rt} \times Green$				
Ventilation $\text{Coeff}_{rt} \times \text{Green}_c$		-0.0880***		-0.0686***
		(0.0177)		(0.0133)
Country-class (cty_c) FE	Yes	Yes	Yes	Yes
Class-year ($c_1 t$ and $c_4 t$) FE	Yes	Yes	Yes	Yes
Region-year (rt) FE	Yes	Yes	Yes	Yes
Observations	1,175,107	1,175,058	1,175,107	1,175,058

Back to main