Measuring the Health Effects of Implicit Air Pollution Trades on the European Carbon Market

Laure de Preux[1] Dana Kassem[2] Ulrich J. Wagner[3]

[1]Imperial College London

[2]Zalando SE

[3]University of Mannheim

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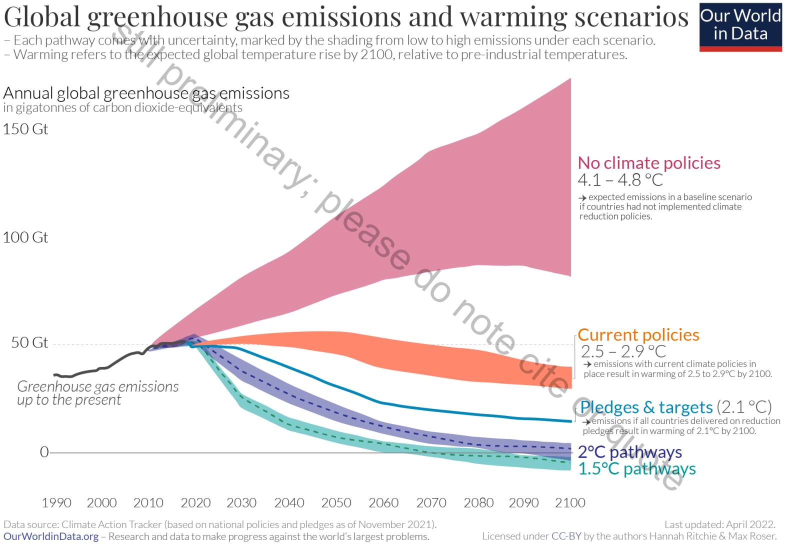
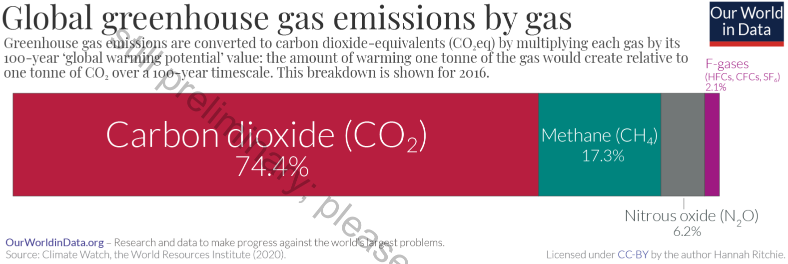
HEAL Project

High mitigation costs hinder progress towards global climate targets



Climate policy targeted at abating carbon dioxide (CO_2)



- Combustion of fossil fuels is main source of CO_2 emissions
- CO_2 jointly emitted with multiple air pollutants
- Abating CO_2 emissions thus reduces harmful co-pollution

$\Rightarrow$ ancillary benefit / co-benefit of climate policy

Direct benefits of CO_2 abatement are global, but co-benefits are local

Implications:

- Co-benefits change net cost of abatement and hence the incentives for global cooperation (e.g. China)
- Within countries and regions, co-benefits are spatially heterogeneous and could thus have significant distributional impacts

Case in point: Decentralized climate policies such as cap-and-trade

Example: Local effects of cap-and-trade (1)

RWE Niederaußem (DE): 26.3 Mt CO_2

$\xrightarrow{1t\,CO_2}$

PGE Belchatow (PL): 29.5 Mt CO_2

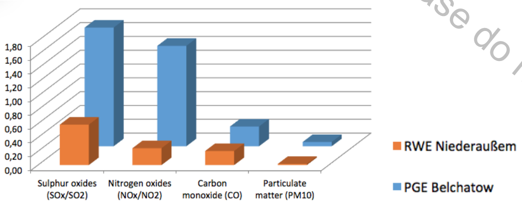
- Market forces shift CO_2 emissions to emitters with highest abatement costs
- Aggregate CO_2 emissions remain constant (**cap**-and-trade)
- Locus of CO_2 emission doesn't matter because damages are global.

Example (2): But implicit co-pollutant trades are not ton-for-ton

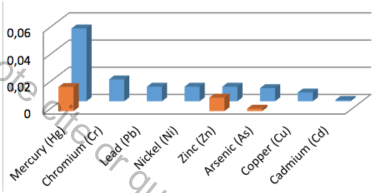
RWE Niederaußem (DE): 26.3 Mt CO_2

$\xrightarrow{1\ t\ CO_2}$

PGE Belchatow (PL) 29.5 Mt CO_2



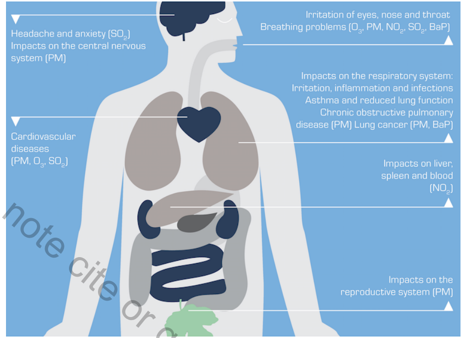
kilograms per ton of CO_2



grams per ton of CO_2 more

Example: Local Effects of cap-and-trade (3)

View of Niederaußem plant from Cologne (1.1 million inhabitants)



Source: European Environment Agency

Adverse health impacts of co-pollution trades scale with population exposed

What this paper does

Research questions

1. How large were air pollution-related health co-benefits associated with mandated CO_2 emissions reductions in the EU carbon market between 2005 and 2015?
2. Did the decentralized cap-and-trade policy for CO_2 emissions deliver greater or smaller co-benefits than centralized (uniform) emissions reductions would have delivered?

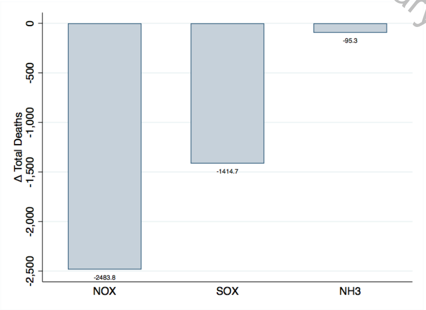
Methods and Contributions

1. Gather comprehensive EU-wide data on co-pollutant emissions at thousands of industrial facilities regulated in the EU ETS
2. Develop an empirical framework for estimating how permit trading affected the spatial distribution of co-pollution emissions
3. Employ novel state-of-the-art model of atmospheric chemical transport to translate co-pollution impact into spatially explicit estimates of co-benefits

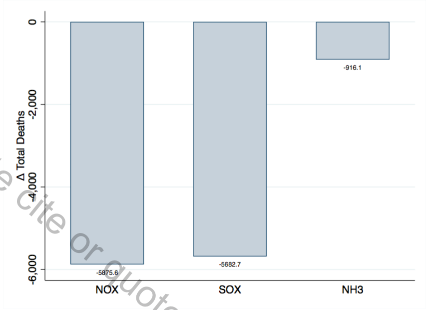
Preview of Main Result

Between 2005 and 2015, EU-wide trading avoided three times more premature deaths due to $PM_{2.5}$ exposure than a counterfactual with uniform emissions reduction.

Figure: Change in $PM_{2.5}$-related Premature Deaths due to 15% reduction in regulated CO_2



(a) Uniform Reduction: -3,994



(b) Cap-and-Trade: -12,474

Related Literature

- Ancillary benefits: 30% to over 100% of the private costs of carbon abatement (Aunan et al. (2007); Burtraw et al. (2003); Ekins (1996); Ekin (1996); Pittel and Rübbelke (2008); Rypdal et al. (2007); van Vuuren et al. (2006); Driscoll et al. (2015); IPCC (2014a); IPCC (2014b))
- Environmental justice: Fowlie et al. (2012), Grainger and Ruangmas (2018); Hernandez-Cortes and Meng (2023), Sheriff (2023)
- Optimal policy design in multipollutant settings when abatement costs are private information (Pittel and Ruebbelke (2008); Ambec and Coria (2013); Bonilla et al. (2017))

The European Union Emissions Trading Scheme (EU ETS)

- Cap-and-trade system for >15.000 stationary CO_2 emitters :
  - Fossil-fuel fired power plants
  - Energy-intensive manufacturing firms
  - (+ Airlines)

- Initial cap > 2 billion tons of CO_2 ($\approx$ half of EU emissions)

- Linear reduction factors 1.74% (2013-2020), 2.2% (2021-)

How does the EU ETS work?

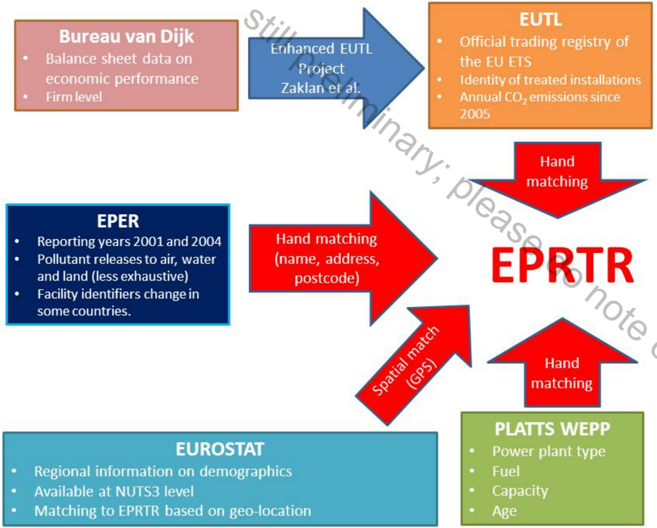
- Define participating emitters (pollutant, sectors, countries, time period)
- Cap the sum of emissions by all participants
- One pollution permit (EUA) entitles holder to emit 1 ton of CO_2 (equivalent)
- Allocation of EUAs to emitters (free-of-charge or via permit auctions)
- Every 12 months: participants report emissions and cancel corresponding amount of EUAs
  - Surplus: sell or bank EUAs
  - Deficit: abate emissions, buy EUAs or borrow them against future allocation.

Data

Main Datasets

1. European Union Transaction Log (EUTL)
   - Register of all ETS installations
   - Verified emissions and permit allocations
   - Years: annual from 2005
2. European Pollutant Release and Transfer Register (E-PRTR)
   - Pollutant releases to air, water and land
   - 91 Pollutants, between 1 and 50 per facility
   - Reporting threshold for pollutant
   - Years: 2001, 2004, annual from 2007

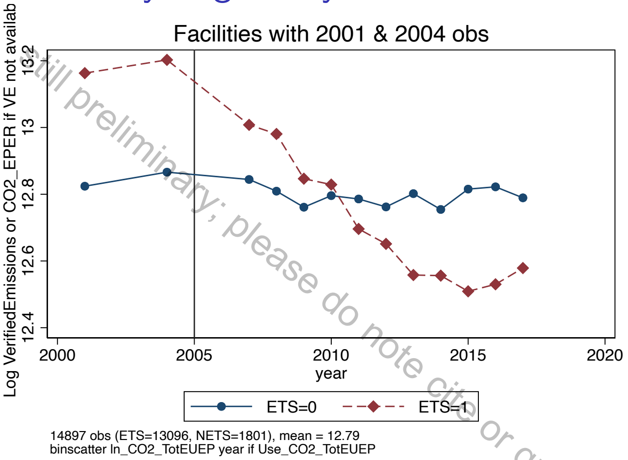
Overview of Data Sources and Entity Linking



Final dataset:

- >8,000 EUTL installations, out of >15,000, matched to EPRTR facilities
- covers 95.5% of EU ETS emissions

Trends in CO_2 Emissions by Regulatory Status



Caveat: Unregulated EPRTR faciliaties with CO_2 emissions below 100,000 tons do not report

more trends

Research Design

Computing Air Pollution Emissions under Different Policies

We consider the **observed cap reduction (2005-15) of 287 Mt (15%)**, implemented in two alternative policies:

I. Uniform Emissions Reduction:

- Each emitter reduces their CO_2 emissions by 15%
- Co-pollution emissions are also scaled in proportion to CO_2, using the median of emitter-specific pollutant-to-CO_2 ratios (observed over multiple years).

II. EU ETS

- Cap reduction by 15% from 2005 levels
- Free permit allocation:
  Observed reduction in free permit allocation ($\gg$15%)
- Permit price P and abatement: Endogenously determined

Economic Model of Facility Emissions under Cap-and-Trade

- Demand for CO_2 by facility i in period t:

$$e\left(P(\Omega_t, \vec{\xi}_t), \omega_{it}, \vec{x}_{it}\right)$$

  - P_t is the price of a permit
  - Ω_t is the cap in year t
  - $\vec{\xi}_t$ price shifters
  - ω_{it} is number of permits obtained free of charge, $(\sum_i \omega_{it} \leq \Omega_t)$
  - $\vec{x}$ demand shifters

- Emissions response to policy parameters Ω and ω_{it}:

$$de_{it} = \frac{\partial e_{it}}{\partial P_t}\frac{\partial P_t}{\partial \Omega_t}d\Omega_t + \frac{\partial e_{it}}{\partial \omega_{it}}d\omega_{it} \tag{1}$$

Econometric approach

Demand for CO_2 emissions at plant i:

$$e_{it} = \alpha_i + \beta P_t + z_i' \beta_z P_t + \beta_\omega \omega_{it} + \mu_{ct} + \theta_{jt} + \nu_{it} \qquad (2)$$

where:

P_t	CO_2 permit price
z_i	emitter characteristics: electricity vs. industry; fuel type; country
ω_{it}	number of permits received free of charge
μ_{ct}	country by year fixed-effect
θ_{jt}	sector by year fixed-effect
α_i	plant fixed effect

Common price effect β not identified.

Identifying the common price effect β

Market clearing on the permit market:

$$\underbrace{E \equiv \sum_{i=1}^{N} e_i \left(P(\Omega), \omega_i\right)}_{\text{Aggregate emissions}} = \underbrace{\Omega \equiv \sum_{i=1}^{N} \omega_i}_{\text{the cap}} \tag{3}$$

Totally differentiate and divide by $d\Omega_t$ (the change in cap):

$$\sum_{i=1}^{N} \frac{\partial e_{it}}{\partial P_t} \cdot \frac{dP_t}{d\Omega_t} + \sum_{i=1}^{N} \frac{\partial e_{it}}{\partial \omega_{it}} \frac{\partial \omega_{it}}{\partial \Omega_t} = 1 \tag{4}$$

Substitute coefficients from (2), $\partial\omega/\partial\Omega = 1/N$ and solve for average price effect β:

$$\beta = \frac{1-\beta_\omega}{N} \left.\frac{dE_t}{dP_t}\right|_{E=\Omega} - \frac{1}{N}\left(\sum_i z_i' \beta_z\right)$$

Calibrating the slope of aggregate permit demand

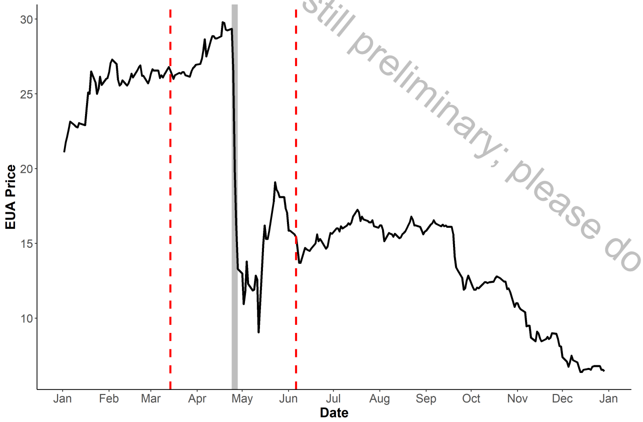


Figure: Permit price crash in April 2006

- Publication of verified emissions revealed that $E(P_0) < \Omega_0 \Rightarrow$ permits were not scarce (see Bushnell et al., 2013)
- Price reaction traces out the slope of aggregate emissions curve E(P)

$$\widehat{\frac{\Delta P}{\Delta \Omega}} \equiv \frac{P_1 - P_0}{\Omega_{2005} - E^*_{2006}} \qquad (5)$$

- take permit prices 6 weeks before (P_0) and after (P_1) publication

Results I: Emissions Changes

Estimates of CO_2 Emissions Demand (Annual Panel Data 2005-17)

VARIABLES	(1) Baseline Model
ω_{it}	0.132***
	(0.027)
P_t	
$\times$ *MANUFACTURING*	-3,050
$\times$ *PP COAL*	-5,480
	(11,858)
$\times$ *PP OTHER*	-2,652
	(7,983)
$\times$ *PP OIL*	1,607
	(6,034)
$\times$ *PP GAS*	6,132
	(8,054)
$\times \omega_i^0$	-0.001
	(0.0009)
Observations	50,222
R-squared	0.958
Country $\times$ Year FE	✓
Industry $\times$ Year FE	✓
Facility FE	✓

Calibrated parameter

Estimates averaged across countries

$$e_{it} = \alpha_i + \beta P_t + z_i' \beta_z P_t + \beta_\omega \omega_{it} + \mu_{ct} + \theta_{jt} + \nu_{it}$$

Notes:

- Permit price is interacted with dummies for emitter group and country.
- Table reports average price coefficients by emitter group
- Manufacturing is the excluded emitter group

Alternative Approach: Carbon Price Elasticities in the Power Sector

- Identify generation elasticity from daily variation in power generation and CO_2 permit prices

For each technology j and country c, model log aggregate generation y on day d as

$$y_{icd} = \mu_c + \beta_c^p p_d + \sum_f \beta_c^f w_{cd}^f + \beta_c^L \log(NET\ LOAD)_{cd} + g(TIME)_{icd} + \xi_{it} \qquad (6)$$

where:

p_d	log CO_2 permit price
w_{cd}^f	log daily price of fossil fuel f

and $g(TIME)$ controls for year, month and weekday.

Daily Generation Data from ENTSO-E Transparency Platform

Table: Daily Panel of Country-by-Fuel Generation; 2015-2021

VARIABLES	(1) mean	(2) sd	(3) min	(4) max	(5) N
EUA permit price	23.4	17.1	3.9	88.9	10,922
Nat. Gas price	25.4	26.3	3.1	451.3	10,922
Coal price	70.0	30.2	34.7	236.7	10,922
Net load	29,255	19,320	2,690	80,245	10,922
Log Generation					
Fossil Gas	8.023	1.036	0.296	10.09	10,922
Hard Coal	7.552	1.707	-8.476	9.907	9,958
Oil	4.209	1.731	-5.075	6.636	4,622
Lignite	9.040	0.526	7.956	9.880	3,391
Ozone season	0.587	0.492	0	1	10,922
EUA price ozone season	14.06	17.47	0	64.66	10,922

Pooled Estimation Results

Dependent variable is log generation

VARIABLES	(1) Lignite	(3) Hard Coal	(5) Oil	(7) Natural Gas
ln P_{CO2}	-0.113	-0.218	0.388	0.300***
	(0.0561)	(0.226)	(0.332)	(0.0473)
ln P_{GAS}	0.194	0.465**	0.00671	-0.237**
	(0.133)	(0.169)	(0.338)	(0.102)
ln P_{COAL}	-0.122	-0.0858	-0.0672	0.0547
	(0.158)	(0.241)	(0.198)	(0.110)
ln Net Load	0.825	3.777*	2.559*	1.857***
	(0.147)	(1.905)	(1.117)	(0.346)
Observations	3,391	9,958	4,622	10,922
R-squared	0.922	0.774	0.595	0.831

Includes FE for country-by-year, month, day of week.
Standard errors clustered at country level
*** p<0.01, ** p<0.05, * p<0.1

Pooled Estimation Results II

Dependent variable is log generation

VARIABLES	(1) Coal	(3) Oil	(5) NatGas
ln P_{CO2}	-0.214	0.388	0.300***
	(0.173)	(0.332)	(0.0473)
ln P_{GAS}	0.426**	0.00671	-0.237**
	(0.135)	(0.338)	(0.102)
ln P_{COAL}	-0.114	-0.0672	0.0547
	(0.180)	(0.198)	(0.110)
ln Net Load	3.428*	2.559*	1.857***
	(1.794)	(1.117)	(0.346)
Country × year FE	Y	Y	Y
Calendar Month FE	Y	Y	Y
Day-of-week FE	Y	Y	Y
Observations	13,349	4,622	10,922
R-squared	0.795	0.595	0.831

Standard errors are clustered at the country level
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Gas-fired Power Generation and CO_2 permit prices

Dependent variable is log generation

VARIABLES	DE	ES	FR	IT	NL	PL	PT
ln P_{CO2}	0.150*	0.272***	0.863***	0.157***	0.244***	0.298***	-0.0935
	(0.0776)	(0.105)	(0.256)	(0.0245)	(0.0465)	(0.0760)	(0.166)
ln P_{GAS}	-0.506***	-0.293**	-0.205	-0.170***	-0.426***	-0.307***	0.258
	(0.0716)	(0.125)	(0.133)	(0.0250)	(0.0432)	(0.0588)	(0.157)
ln P_{COAL}	-0.0235	0.483***	-0.541***	0.150***	-0.0262	0.360***	-0.203
	(0.0893)	(0.153)	(0.165)	(0.0305)	(0.0726)	(0.0695)	(0.222)
ln Net Load	1.923***	3.378***	4.359***	1.610***	2.484***	0.514***	2.558***
	(0.231)	(0.278)	(0.318)	(0.0566)	(0.255)	(0.196)	(0.554)
Observations	1,718	1,109	800	1,716	1,725	1,655	1,082
R-squared	0.535	0.522	0.523	0.930	0.507	0.748	0.330

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

Coal-fired Power Generation and CO_2 permit prices

Dependent variable is log generation

VARIABLES	DE	ES	FR	IT	NL	PL	PT
$\ln P_{CO2}$	-0.172***	0.897***	0.383	0.0444	-0.514***	0.00389	0.108
	(0.0590)	(0.114)	(1.729)	(0.0515)	(0.0481)	(0.0299)	(0.252)
$\ln P_{GAS}$	0.551***	-0.0170	-1.789*	0.0316	0.684***	0.0417*	0.641**
	(0.0530)	(0.107)	(0.977)	(0.0475)	(0.0519)	(0.0252)	(0.264)
$\ln P_{COAL}$	-0.504***	0.878***	2.416**	0.0452	-0.373***	0.00463	-0.966***
	(0.0702)	(0.141)	(0.972)	(0.0650)	(0.0642)	(0.0351)	(0.299)
ln Net Load	1.837***	1.487***	7.085***	0.781***	0.493**	1.606***	1.526**
	(0.227)	(0.309)	(1.672)	(0.108)	(0.206)	(0.112)	(0.632)
Observations	3,436	1,109	527	1,716	1,722	3,346	656
R-squared	0.375	0.856	0.590	0.616	0.666	0.182	0.392

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

Computing Emissions for a Tightening of the Cap by 15%

Step 1: Assume changes in cap and free allocation:

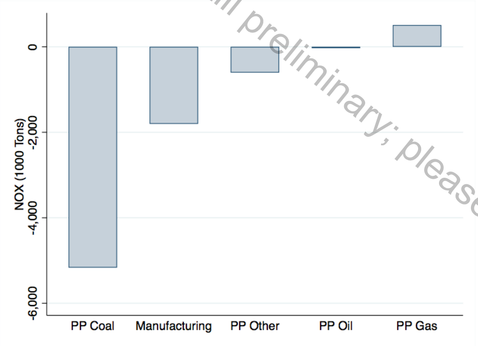
$$\Delta\Omega = -0.15\Omega_0$$
$$\Delta\omega_i = \omega_{i,2015} - \omega_{i,2005}$$

Step 2: Simulate resulting changes in emissions of CO_2 and of co-pollutant p

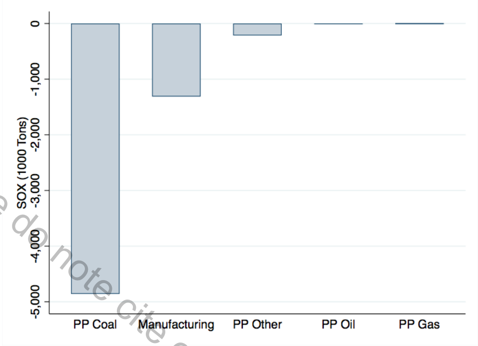
$$\Delta\widehat{e_i} = \left(\hat{\beta} + z_i'\hat{\beta}_z\right) \underbrace{\frac{\Delta\Omega}{-1.48}10^{-7}}_{\Delta P \approx +19.4} + \hat{\beta}_2 \Delta\omega_i$$

$$\Delta\widehat{x_i^p} = \Delta\widehat{e_i} \cdot \underbrace{\left[\frac{x_{it}^p}{e_{it}}\right]_{p50}}_{\text{median emissions ratio}}$$

Change in Co-pollutant Emissions by Emitter Type (Cap-and-Trade)

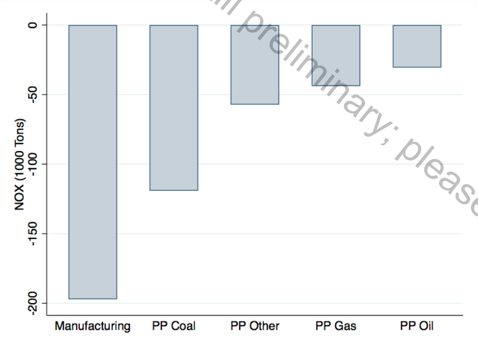


(a) Nitrogen Oxides

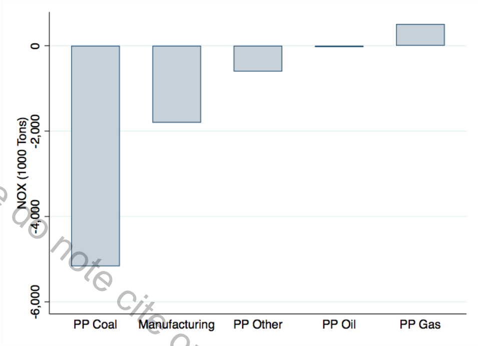


(b) Sulfur Oxides

Change in NO_x Emissions by Emitter Type (Trading vs. Uniform)

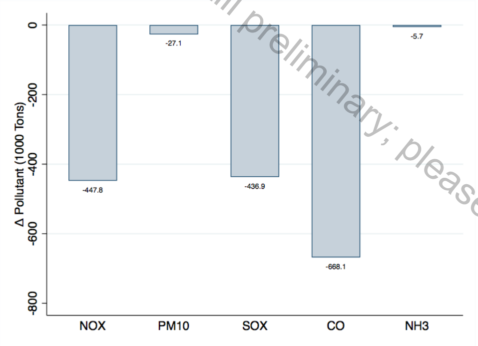


(a) Uniform Reduction

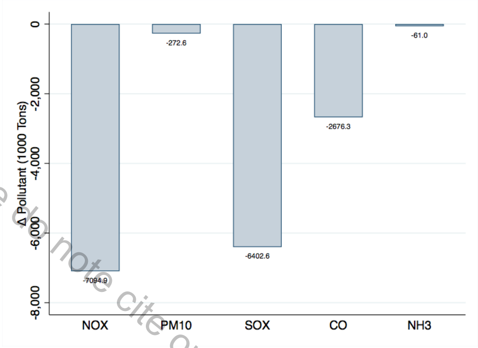


(b) Cap-and-Trade

Changes in Emissions of Main Co-pollutants (Trading vs. Uniform)



(a) Uniform Reduction



(b) Cap-and-Trade

Aggregating Pollution Changes to Co-Benefits

Compute co-benefits using pollution-specific environmental cost estimates

Employ pollutant-specific environmental costs

$$\delta^p \left[\frac{€}{\text{kg}}\right]$$

to sum damages across pollutants:

$$\sum_p x_p \delta^p$$

Price δ^p is the mid-point estimate of health damages resulting from 1 kg of pollutant p being released by the average emitter in the EU-28 countries.
Data from De Bruyn et al. (2018).

Counterfactual Change in Environmental Damages (bn. EUR)

	Δ Damages	
	Unweighted	Pop-Weighted
A. Power Plants	-156.8	-79.0
Natural Gas	7.5	5.5
Oil	-2.1	-3.2
Coal	-150.0	-73.9
Other	-12.3	-7.5
B. Manufacturing	-67.9	-56.8
Total	**-224.7**	**-135.8**

Counterfactual Change in Environmental Damages (bn. EUR)

	Δ Damages	
	Unweighted	Pop-Weighted
A. Power Plants	-156.8	-79.0
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Oil	-2.1	-3.2
Coal	-150.0	-73.9
Other	-12.3	-7.5
B. Manufacturing	-67.9	-56.8
Total	**-224.7**	**-135.8**
vs. uniform 15% reduction	**-16.9**	**-16.1**

- Trading increases co-benefits by factor of more than eight
- Owing to much stronger abatement at coal-fired power plants and manufacturing

Getting atmospheric pollution dispersion right

Environmental prices:

+ easy to use

+ broad pollutant coverage

- omit complexity of atmospheric pollution dispersion, which is governed by highly non-linear function of atmospheric chemistry, weather, topography

▶ We care about atmospheric dispersion because spatial heterogeneity in pollution exposure could strongly affect results

Solution: Combine econometric model with state-of-the-art **Chemical Transport Model**

Results II: Atmospheric Dispersion and Population Exposure

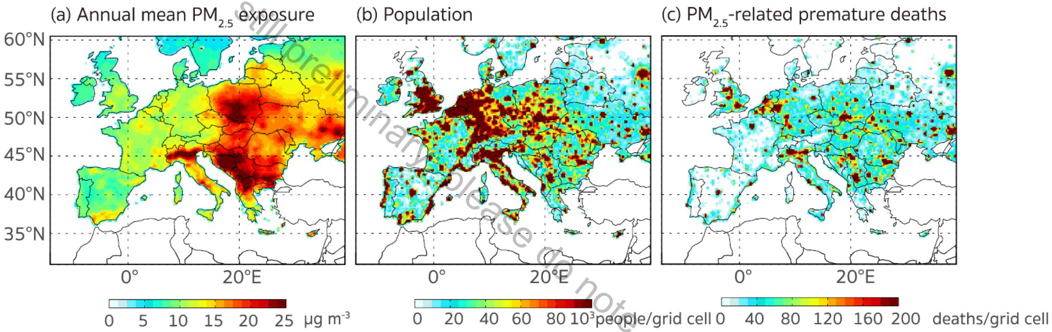
A Nested GEOS-Chem Adjoint model for Europe

- Chemical Transport Model built by HEAL-Project team (Gu et al., 2023a,b)
- Input: Primary pollutants NO_x, SO_2, NH_3, (...)
- Outputs:
  - Gridded (0.25° × 0.3125°) population exposure to $PM_{2.5}$, O_3
  - Source appointment: Sensitivity of exposure to grid-level emissions more
- Gu et al. (2023a) combine population exposures with *Global Burden of Disease 2019* (Murray et al., 2020) to estimate pollution-related premature deaths:

$$J_{PM_{2.5}} = \sum_{L} \sum_{A} \sum_{k \in D} \sum_{(I,J) \in k} \left(POP_{I,J,A} \times MOR_{I,J,A,L} \times AF_{I,J,A,L} \right)$$

where $AF_{I,J,A,L} = \frac{RR_{I,J,A,L} - 1}{RR_{I,J,A,L}}$ and L∈{COPD, IHD, LRI, LC, T2D, stroke}

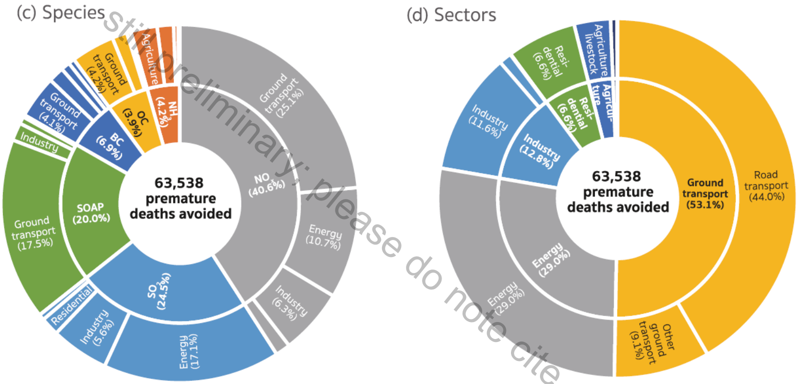
$PM_{2.5}$ exposure, population, and health burden in Europe



Source: Gu et al. (2023a)

- 449,813 $PM_{2.5}$-related premature deaths in 2015 (relative to total pop. 598.97m)
- 265,328 deaths (59%) due to anthropogenic NO_x, NH_3, SO_2, OC, BC, SOAP

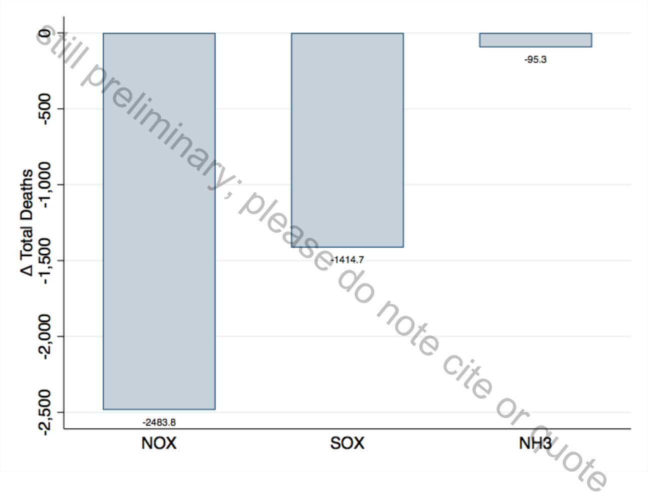
Health Benefits of Reducing Anthropogenic PM2.5 Pollution, 2005-2015



Source: Gu et al. (2023a)

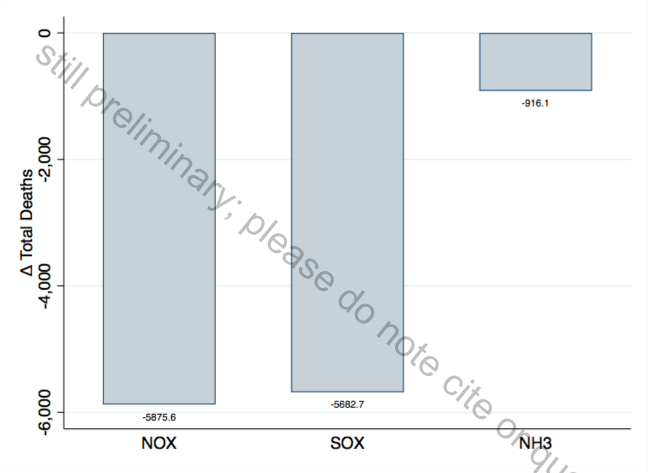
- Energy and Industry account for 26,558 (42%) of avoided deaths
- What was the contribution of the EU ETS?

Change in $PM_{2.5}$-related deaths: Uniform emissions reductions



Net change in premature deaths: -3,994.

Change in $PM_{2.5}$-related deaths: With permit trading



- **Net change in premature deaths: -12,474**.
- **Trading gives 3x larger reduction in premature deaths than uniform reduction**.

Implications of Co-Benefits Estimates for Cost-Benefit Analysis

1. Co-benefits vs. direct benefits

- Assume **€190/tCO_2** per ton for the social cost of carbon (Rennert *et al*, 2022 *nature*)
- Assume low VSL of €2.7m: 'Co-pollutant cost of carbon': **€117/tCO_2**

⇒ **$PM_{2.5}$-related health co-benefits are on par with direct benefits**

2. Co-benefits vs. abatement costs

- Marginal abatement costs are bounded from above by the carbon price
- Upper bound on abatement costs:

$$287\,Mt \cdot \frac{€30}{t} = €\,8.6 \text{ bn}$$

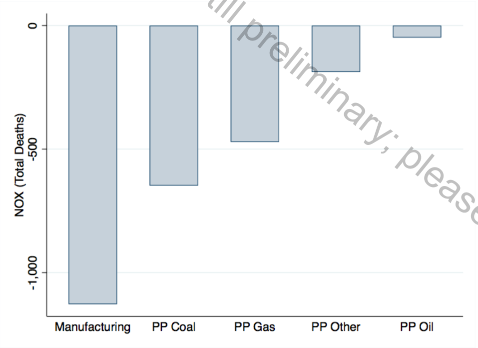
- private benefit-to-cost ratio

$$\frac{33.6 \cdot 10^9}{8.6 \cdot 10^9} = 3.9$$

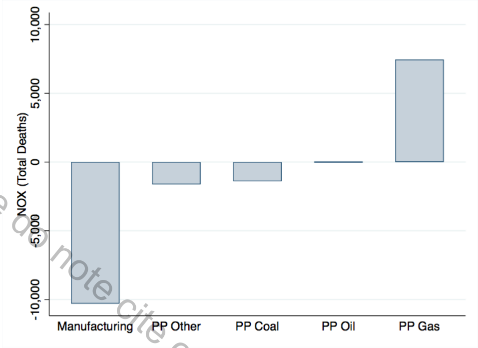
⇒ **EU ETS is very cost effective.**

Spotlight I: Distributional Issues: NOx Hotspots change

Changes in PM2.5-related Premature Deaths by NOx Emitter (Trading vs. Uniform)



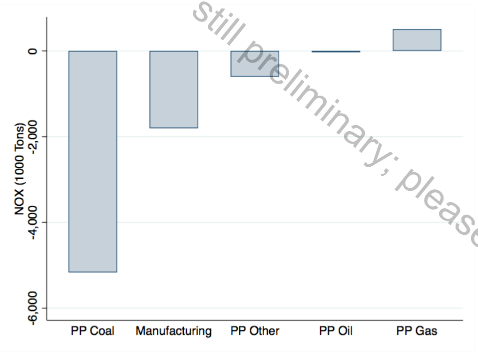
(a) Uniform Reduction



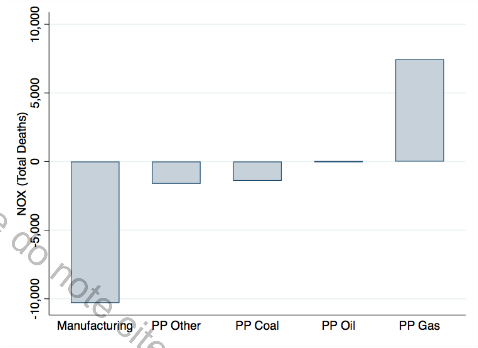
(b) Cap-and-Trade

Analyzing distribution of health co-benefits and co-damages requires CTM forward runs (computationally expensive).

Spotlight II: Why the CTM matters – NO_x emissions vs. damages



(a) NO_x Emissions

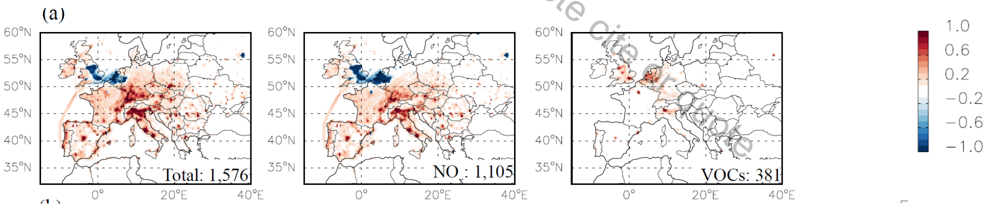


(b) Premature Deaths due to NO_x

Accounting for atmospheric chemistry and population exposure changes the ranking of which one is the worst NO_x emitter group.

Spotlight III: Health Burden of NO_x co-emissions beyond $PM_{2.5}$

- NO_x is the main precursor to **ozone pollution**, along with CO and volatile organic compounds (VOCs)
- Calls for assessment of ozone-related health burden.
- Challenging because of seasonality and non-linearity of ozone formation
- Could lead to different conclusions because NO_x sensitivity of ozone is negative in NO_x-saturated regions (Gu et al., 2023b):



Conclusions

- The EU ETS redistributed air pollution in major ways across space
- Valuation of co-pollution changes implies high (private) benefit-cost ratio of EU ETS
- $PM_{2.5}$ related Co-benefits on par with direct benefits of CO_2 abatement
- Combining econometric model with CTM yields sizable mortality reductions
- Letting polluters trade CO_2 increases co-benefits three-fold relative to uniform reductions.

Thank you

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