# Green Innovation and Climate Policies

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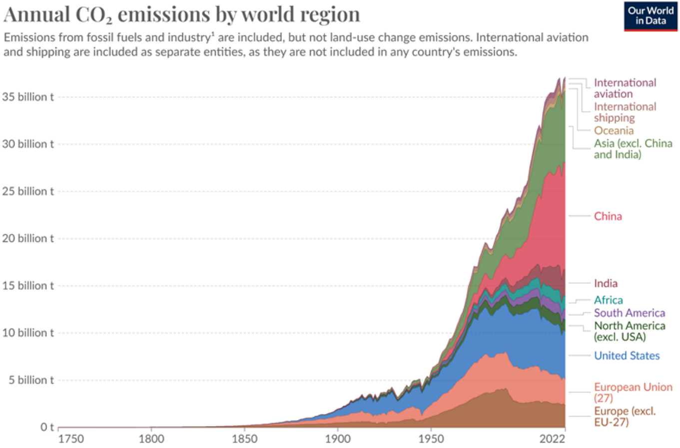
May 2024

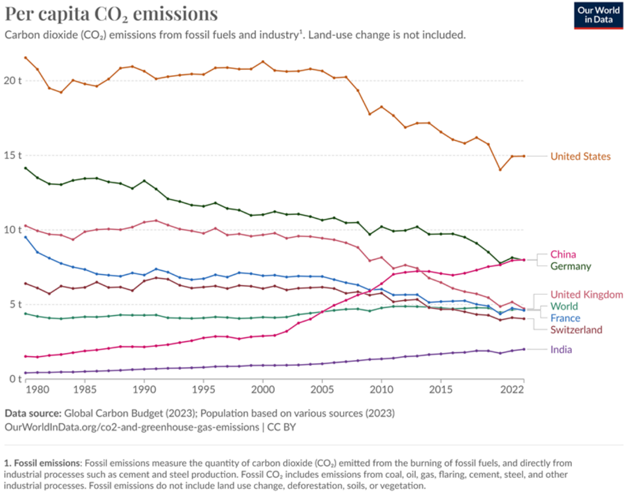
# While global emissions are still increasing




**Data source:** Global Carbon Budget (2023) OurWorldInData.org/co2-and-greenhouse-gas-emissions | CC BY

1. **Fossil emissions:** Fossil emissions measure the quantity of carbon dioxide ($CO_2$) emitted from the burning of fossil fuels, and directly from industrial processes such as cement and steel production. Fossil $CO_2$ includes emissions from coal, oil, gas, flaring, cement, steel, and other industrial processes. Fossil emissions do not include land use change, deforestation, soils, or vegetation.

# Some countries are much cleaner / getting cleaner




- Adjusting for trade gives similar trends.

# How to reduce emissions?

- Kaya's identity decomposes emissions in

$$\text{Emissions} = \text{Pop} \times \frac{\text{GDP}}{\text{Pop}} \times \frac{\text{Energy}}{\text{GDP}} \times \frac{\text{Emissions}}{\text{Energy}}$$

- To reduce emissions at the lowest possible cost, one would like to:
  - improve energy-efficiency (reduce Energy / GDP);
  - make energy cleaner (reduce Emissions / Energy).
- In a broad sense, choices on the direction of technology largely explain the differences in CO2 emissions per capita between (otherwise) similar countries.

# DTC literature

- Initially, climate macro literature focused on models with exogenous technological progress (Nordhaus' DICE model).
  - In such framework, getting the carbon price right is often the most important policy question.
- Mounting evidence that the direction of technology is endogenous and that innovation responds to policy.
- Directed Technical Change (DTC) literature takes the endogeneity of innovation as a starting point:
  - Policies must be designed with their consequences on innovation in mind.
  - Clean vs dirty innovation: Acemoglu, Aghion, Bursztyn, and Hémous (2012), etc.
  - Energy-saving vs energy-using innovation: Smulders and de Nooij (2003), Hassler, Krusell, Olovsson (2021), etc.

# Roadmap

1. **Empirical evidence**
2. Clean vs dirty innovation
3. Energy using vs energy-saving innovation
4. Applications of DTC framework

# Aghion, Dechezleprêtre, Hémous, Martin and van Reenen (2016)

- Aghion, Dechezleprêtre, Hémous, Martin and van Reenen (2016) test for DTC in the car industry:
  - Do higher gas prices lead to more clean and fewer dirty innovations?
  - In addition, they establish that there is *path-dependence* both at the firm and the country level.
- Build new patent data set on innovations in the car industry at the firm level from 1978-2005 (using PATSTAT):
  - Clean innovation = electric, hybrid and hydrogen vehicles;
  - Dirty innovation = fossil fuel engines.
- Key: manufacturers from the car industry sell to multiple markets.
  - Hence possible to build a firm-specific fuel price.

# Econometric approach

- Run panel Poisson regression:

$$PAT_{C,it} = \exp\left(\begin{array}{c} \beta_{C,P} \ln FP_{it-2} + \beta_{C,KC} \ln K_{C,it-2} \\ +\beta_{C,KD} \ln K_{D,it-2} + \beta_{C,SC} \ln SPILL_{C,it-2} \\ +\beta_{C,SD} \ln SPILL_{D,it-2} + \eta_{\mathrm{Ci}} + \delta_t \end{array}\right) + u_{C,it}$$

  - $PAT_{C,it}$ is the flow of clean patents filed by firm $i$ in year $t$;
  - $FP_{it}$ the fuel price for *firm i*
  - $K_{C,it}$: the stock of clean patents of the firm.
  - $SPILL_{C,it}$: the stock of clean patents in the “countries” of the firm (a measure of spillovers).
  - $\eta_{\mathrm{Ci}}$ is a firm fixed effect and $\delta_t$ year fixed effects.
- Add controls at the firm level: GDP per capita, electricity price...
- And similarly for dirty patents $PAT_{D,it}$.

# Firm specific prices and spillovers

- Build a firm $i$'s specific fuel price:

$$FP_{i,t} = \sum_c \omega_{i,c} FP_{c,t}$$

  - $FP_{c,t}$ is the fuel price in a country (data on 25 countries)
  - $\omega_{i,c}$ is the weight of country $c$ for firm $i$, computed using a firm's patent history pre-sample (as a proxy for firm's market shares) adjusted by $GDP_c$.
  - Use fuel tax instead of fuel price in robustness checks.

- Similarly build firm-specific spillovers by combining country level stocks with the pre-sample distribution of firms' inventors.

# Path dependence and DTC

TABLE 3
REGRESSIONS OF CLEAN AND DIRTY PATENTS

| | DEPENDENT VARIABLE: CLEAN PATENTS | | | DEPENDENT VARIABLE: DIRTY PATENTS | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Fuel price (ln *FP*) | .970*** | .962** | .843** | −.565*** | −.553*** | −.551*** |
| | (.374) | (.379) | (.366) | (.146) | (.205) | (.194) |
| R&D subsidies (ln R&D) | | −.005 | −.006 | | −.006 | −.005 |
| | | (.025) | (.024) | | (.021) | (.020) |
| Emission regulation | | | −.008 | | | .04 |
| | | | (.149) | | | (.120) |
| Clean spillover (ln $\text{SPILL}_C$) | .268*** | .301*** | .266*** | −.093* | −.078 | −.089 |
| | (.076) | (.087) | (.088) | (.048) | (.067) | (.063) |
| Dirty spillover (ln $\text{SPILL}_D$) | −.168** | −.207** | −.165* | .151** | .132 | .138* |
| | (.085) | (.098) | (.098) | (.064) | (.082) | (.077) |
| Own stock clean (ln $K_C$) | .306*** | .320*** | .293*** | −.002 | −.004 | .021 |
| | (.026) | (.027) | (.025) | (.022) | (.022) | (.020) |
| Own stock dirty (ln $K_D$) | .139*** | .135*** | .138*** | .557*** | .549*** | .539*** |
| | (.017) | (.017) | (.017) | (.031) | (.022) | (.017) |
| Observations | 68,240 | 68,240 | 68,240 | 68,240 | 68,240 | 68,240 |
| Firms | 3,412 | 3,412 | 3,412 | 3,412 | 3,412 | 3,412 |

NOTE.—Standard errors are clustered at the firm level. Estimation is by the CFX method. All regressions include controls for GDP per capita, year dummies, fixed effects, and three dummies for no clean knowledge, no dirty knowledge, and no dirty or clean knowledge (in the previous year). Fuel price is the tax-fuel price faced. R&D subsidies are public R&D expenditures in energy-efficient transportation. Emissions regulations are maximum levels of tailpipe emissions for pollutants from new automobiles.

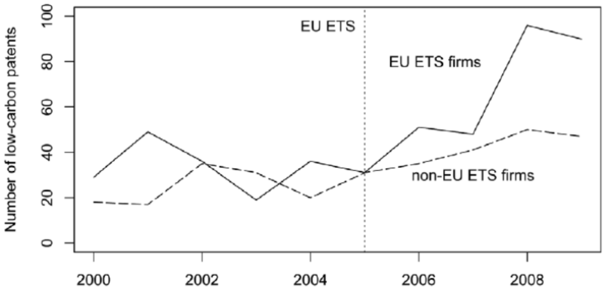
# Further results

- Separate dirty patents into grey patents (which improves energy efficiency) and purely dirty patents (which do not):
  - Effect on grey is positive non-significant (elasticity below 0.3).
  - Effect on purely is negative with larger magnitude (around $-0.8$).
- Clean cars use electricity as an input: high electricity prices discourage clean innovation.
- Aghion, Bénabou, Martin, and Roulet (2023) use a similar framework to test the effect of consumers' environmental preferences and competition.
  - Consumers' pro-environmental preferences lead to more clean innovation particularly where the industry is more competitive.

# Calel and Dechezleprêtre (2016)

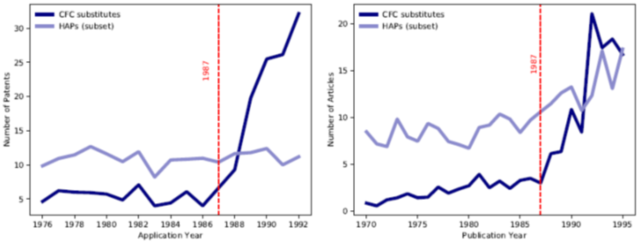
- Calel and Dechezleprêtre (2016): EU-ETS (European cap-and-trade system) increased green innovation by 10%
  - Only sufficiently large establishment are subject to EU-ETS;
  - They compare firms subject to EU-ETS with similar firms not subject to EU-ETS.

FIGURE 5.—LOW-CARBON PATENTS BY MATCHED EU ETS AND NON–EU ETS FIRMS



# Dugoua (2022)

- In the 80s, CFC emissions were causing a reduction in the ozone layer.
- Countries reached an agreement at Montreal in 1987 to progressively reduce CFCs.
- Dugoua (2022) compares the evolution of patents and scientific articles on CFC substitutes versus other similar chemicals.+




(a) Patents (b) Articles

FIGURE 4
Pre-Trends in Counts of Documents Mentioning CFC Substitutes and HAPs

*Note:* The graphs display the pre-trends for the treated group (CFC substitutes) and the control group constructed using a subset of the HAP molecules that have counts and pre-trends closest to the average CFC substitutes.

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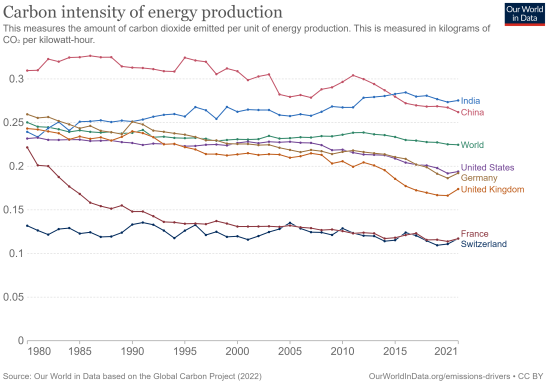
# Acemoglu, Aghion, Bursztyn and Hémous (2012, AABH)

- AABH provide the first DTC model to study the development of clean technologies that substitute for dirty ones.
  - Electric vs fossil fuel vehicles; renewables vs fossil fuel power plants.
- How does the endogeneity of innovation affect optimal climate policy?



# Production

- Final good $Y_t$ produced competitively with a clean intermediate input $Y_{ct}$, and a dirty input $Y_{dt}$

$$Y_t = \left[ Y_{ct}^{\frac{\varepsilon-1}{\varepsilon}} + Y_{dt}^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}}.$$

  - Assume $\varepsilon > 1$, the two inputs are substitute.
- For $j \in \{c, d\}$, input $Y_{jt}$ produced competitively with labor $L_{jt}$ and a continuum of machines $x_{jit}$:

$$Y_{jt} = L_{jt}^{1-\alpha} \int_0^1 A_{jit}^{1-\alpha} x_{jit}^{\alpha} di.$$

  - Machines produced monopolistically with the final good (1 for 1).
- Labor market clearing $L_{ct} + L_{dt} = L$.
- Production of dirty input depletes environmental stock $S$:

$$S_{t+1} = -\xi Y_{dt} + (1+\delta) S_t \text{ if } S \in (0, \bar{S}). \quad (1)$$

  - An increase in $A_{ct}/A_{dt}$ reduces emissions.

# Innovation technology

- At the beginning of every period scientists (of mass $S = 1$) work to innovate in the clean or the dirty sector.
  - Given sector choice, each randomly allocated to one machine in their target sector (not essential).
- Every scientist has a probability $\eta_j$ of success (without congestion).
  - if successful, proportional improvement in quality by $\gamma > 0$ and the scientist gets monopoly rights for one period,

$$A_{jit} = (1 + \gamma) A_{ji(t-1)}.$$

  - otherwise monopoly rights in that machine randomly allocated to an entrepreneur who uses technology $A_{jit} = A_{ji(t-1)}$.
- Therefore, if $s_{jt}$ scientists innovate in $j$, the law of motion of quality of input in sector $j \in \{c, d\}$ is:

$$A_{jt} = \left(1 + \gamma\eta_j s_{jt}\right) A_{jt-1}.$$

- Assumption that monopoly rights only last for one period is not essential but simplifies the analysis.

# Innovation allocation

- Innovators target the sector with the highest expected profits $\Pi_{jt}$:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d}\frac{1+\gamma\eta_d s_{dt}}{1+\gamma\eta_c s_{ct}}\frac{p_{ct}Y_{ct}}{p_{dt}Y_{dt}} \tag{2}$$

$$= \frac{\eta_c}{\eta_d}\underbrace{\left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}}}_{\text{price effect}}\underbrace{\frac{L_{ct}}{L_{dt}}}_{\text{market size effect}}\underbrace{\frac{A_{ct-1}}{A_{dt-1}}}_{\text{direct productivity effect}}$$

  - Because of the Cobb-Douglas structure, monopolist earn a constant share of their sector's revenues.
  - Relative revenues can be decomposed into relative prices, labor, and technologies.
  - Relative prices and labor themselves depend on technologies.

# First lesson: path dependence

- Therefore, we can write the ratio of expected profits as:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d}\left(\frac{1+\gamma\eta_c s_{ct}}{1+\gamma\eta_d s_{dt}}\right)^{\sigma-2}\left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\sigma-1} \quad (3)$$

$$\text{with } \sigma - 1 \equiv (1-\alpha)(\varepsilon-1) \quad (4)$$

  - Innovation allocation is a corner solution if $A_{c(t-1)}/A_{d(t-1)}$ is sufficiently large or small.

- There is path dependence in innovation: innovation favors the relatively more advanced sector.
  - If $A_{d0}$ is sufficiently advanced relative to $A_{c0}$, then innovation is entirely directed towards dirty technologies in laissez-faire.

- In laissez-faire, the economy does NOT converge toward a BGP.

# Second lesson: policy can redirect innovation

- Subsidy to clean innovation $q_t$ directly boosts the return to innovating in clean.
- A carbon tax $\tau$ reduces the price of the dirty input.

$$\frac{\Pi_{ct}}{\Pi_{dt}} = (1+q_t)\frac{\eta_c}{\eta_d}\left(\frac{p_{ct}}{\widehat{p}_{dt}}\right)^{\frac{1}{1-\alpha}}\frac{L_{ct}}{L_{dt}}\frac{A_{ct-1}}{A_{dt-1}}$$

$$= (1+\tau_t)^{\varepsilon}(1+q_t)\frac{\eta_c}{\eta_d}\left(\frac{1+\gamma\eta_c s_{ct}}{1+\gamma\eta_d s_{dt}}\right)^{\sigma-2}\left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{\sigma-1}$$

- A sufficiently large subsidy $q_t$ ensures that innovation occurs in the clean sector.
  - If subsidy is maintained for a sufficiently long period, $A_{ct}$ will catch-up with and eventually overtake $A_{dt}$;
  - afterwards market forces will push towards clean innovations.
- A carbon tax can also redirect innovation but it will also affect production.

# Third lesson: redirecting growth and costs of delay

- Growth follows

$$g_t = \frac{p_{ct} Y_{ct}}{Y_t} \gamma \eta_c s_{ct} + \frac{p_{dt} Y_{dt}}{Y_t} \gamma \eta_d s_{dt}$$

  - Growth is higher when innovation targets the more advanced sector.
  - Intuitively: the two inputs are substitute, re-inventing how to produce energy is useless (except for the climate externality).

- The energy transition is costly: growth is low when $A_{ct}$ is catching up with $A_{dt}$.
- Third lesson delaying the intervention is costly: if the social planner waits before redirecting innovation, the cost of intervention increases.

# Fourth lesson: two instruments

- 4th lesson: Optimal policy involves both a carbon tax and research subsidies.
- Social planner is more forward looking than the market:
  - here because of 1 period monopoly rights but more generally patents expire at some point;
  - + “building on the shoulders-of-giants" - externality.
- This is true for both clean and dirty but we need to transition away from dirty towards clean:
  - High share of social value from improving solar panels today comes from getting better social panels tomorrow. Not captured by innovator
  - High share of social value from improving natural gas power today comes from the profits today. Captured by the innovator.
  - Today’s dirty innovations will be useless in 50 years while today’s clean innovation will be the backbone of the economy.
- Share of private value to social value lower for clean technology: Market failure.
  - Even with infinite patents, even with Pigovian taxation.

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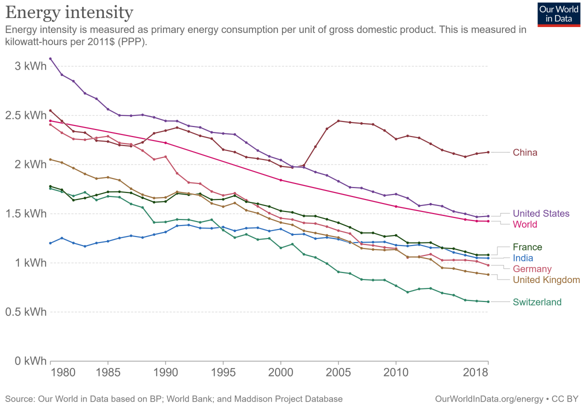
# Energy saving technological change

- Alternatively, one can think of reducing the use of energy.
  - Models of DTC between energy-saving vs energy-using innovation.
  - Decoupling between GDP and energy use is happening.



# Substitution between energy and other inputs

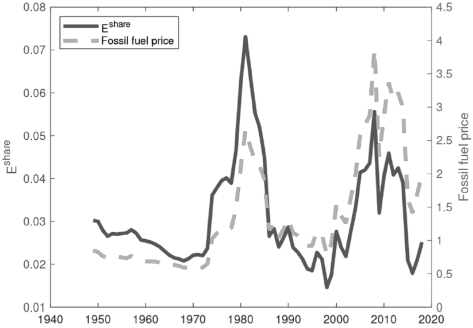



FIG. 1.—Fossil prices (in chained 2005 US dollars) and the fossil energy share of income.

source:Hassler, Krusell and Olovsson (2021)

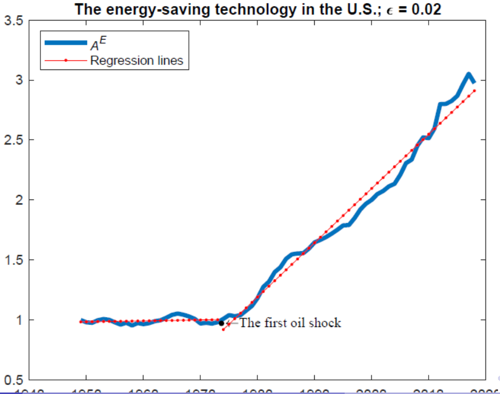
- In the short-run, energy seems Leontieff with other inputs;
- but in the long-run, the energy share is roughly constant (Cobb-Douglas).

# Macroevidence of DTC

- Hassler, Krusell and Olovsson (2021) assume

$$Y_t = \left[ \left( A_{Pt} K_t^{\alpha} L_t^{1-\alpha} \right)^{\frac{\varepsilon-1}{\varepsilon}} + \left( A_{Et} E_t \right)^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}} \text{ with } \varepsilon < 1.$$

  - With $\varepsilon < 1$, $A_{Et}$ is energy-saving and an increase in $A_{Et}/A_{Pt}$ reduces the relative demand for energy (vs $K$ and $L$).



# Simple model of energy-saving innovation

- Keep the same structure as in AABH (Hémous and Olsen, 2021):

$$Y(t) = \left[ Y_P(t)^{\frac{\varepsilon-1}{\varepsilon}} + Y_E(t)^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}} \text{ with } \varepsilon < 1.$$

- Production input $Y_{Pt}$ is produced with labor and a continuum of machines $x_{Pit}$:

$$Y_{Pt} = L_t^{1-\alpha} \int_0^1 A_{Pit}^{1-\alpha} x_{Pit}^{\alpha} di.$$

- Energy-services $Y_E$ are similarly produced with energy $E_t$ and a continuum of machines $x_{E,it}$:

$$Y_{Et} = E_t^{1-\alpha} \int_0^1 A_{E,it}^{1-\alpha} x_{E,it}^{\alpha} di.$$

- Same innovation technology as in AABH.

# Innovation allocation

- Innovators target the sector with the highest expected profits:

$$\frac{\Pi_{Pt}}{\Pi_{Et}} = \frac{\eta_P\left(1+\gamma\eta s_{Et}\right)}{\eta_E\left(1+\gamma\eta s_{Pt}\right)}\frac{p_{Pt}Y_{Pt}}{p_{Et}Y_{Et}} = \frac{\eta_P}{\eta_E}\left(\frac{p_{Pt}}{p_{Et}}\right)^{\frac{1}{1-\alpha}}\frac{L_t}{E_t}\frac{A_{Pt-1}}{A_{Et-1}}$$

$$= \frac{\eta_P\left(1+\gamma\eta s_{Et}\right)}{\eta_E\left(1+\gamma\eta s_{Pt}\right)}\left(\frac{L_t}{E_t}\frac{A_{Pt}}{A_{Et}}\right)^{\frac{\sigma-1}{\sigma}}$$

- With $\varepsilon < 1$, $\sigma < 1$: the price effect now dominates and innovation favors the more backward technology adjusted for factor supply:
  - An oil shock (i.e. a decrease in $E_t$) increases energy-saving innovation;
  - A tightening cap on energy, or resource exhaustion (i.e. a decreases in $E_t$ over time) leads to permanently more energy-saving innovation;
  - The economy converges toward a BGP where $A_{Pt}L_t$ and $A_{Et}E_t$ grow at the same rate.

# Consequences of a BGP

- On a BGP:

$$\frac{\Pi_{Pt}}{\Pi_{Et}} = 1 \Rightarrow \frac{p_{Et} Y_{Et}}{p_{Pt} Y_{Pt}} = \frac{\eta_P \left(1 + \gamma \eta s_{Et}\right)}{\eta_E \left(1 + \gamma \eta s_{Pt}\right)} \approx \frac{\eta_P}{\eta_E}$$

  - The energy share is (nearly) constant in the long-run: the economy looks Cobb-Douglas in the long-run.
- With climate externality, both the social planner solution and the decentralized economy converge toward a BGP.
  - Carbon tax can ensure that $E_t$ decreases at the right pace;
  - The asymptotic innovation allocation is the same for the market and the planner: $g_L + g_{A_P} = g_E + g_{A_E}$
- Role for energy-saving research subsidies is much weaker;
  - No guarantee that the optimal policy involves a subsidy to energy-saving innovation.

# Casey (2024)

- Can we just assume that energy is Cobb-Douglas then to evaluate climate policy?
- Casey (2024) says no:
  - Such an approximation leads to significantly overestimate the emission reductions associated with a given carbon tax along the transition.

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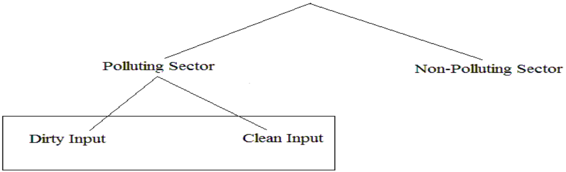
# Hémous (2016)

- Climate negotiations have had limited results: no satisfactory global agreement in sight.
    - Countries have started to move to unilateral policies, with, more and more, call for "green" protectionism.
    - Can unilateral policies from a subset of committed countries ensure sustainable growth? Is protectionism a necessary condition?
- 2 countries (North and South):
    - North may undertake unilateral policies.
- 2 tradeable sectors: energy-intensive (polluting) and non-energy intensive (non-polluting).
    - Energy-intensive good can be produced in a clean or dirty way.



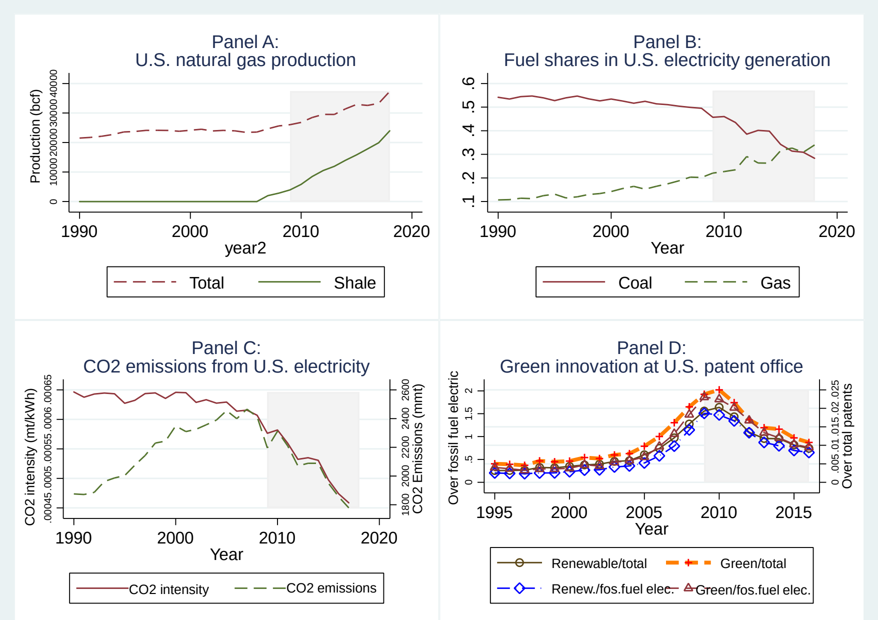
# Key mechanisms

- Local innovation, directed towards non-polluting sector, clean or dirty technologies.
- Comparative advantage depends on:
  - relative productivities in polluting versus non-polluting sector.
  - policies: a carbon tax tends to reduce the compartive advantage in the polluting good.
- Incentive to innovate in a (sub)sector proportional to the total revenue generated by the (sub)sector.
  - Path dependence in clean versus dirty innovation as in AABH.
  - Amplification of comparative advantages: as a country exports a good it has a larger market in that good and tends to innovate more there.
  - Potentially mitigated by international knowledge spillovers.

# Policies' effects

- Static pollution haven effect:
  - A carbon tax in the North leads to a relocation of production in the South.
  - Emissions decrease in the North but increase in the South.
- Dynamic pollution haven effect:
  - The relocation of the energy-intensive good to the South favors innovation in the dirty sector.
  - With a small market, clean innovation in the North may fail to take up.
  - Global emissions may actually increase!
- Green industrial policy: combine subsidies in green technologies with a trade tax in the North.
  - The North can develop clean technologies without losing the energy-intensive good production to the South.
  - Eventually emissions decrease in both countries;
  - either because the North exports the energy-intensive good (reversal of comparative advantage);
  - or because the South also switch to clean innovation because of knowledge spillovers.

# Acemoglu, Aghion, Barrage and Hémous (2023)

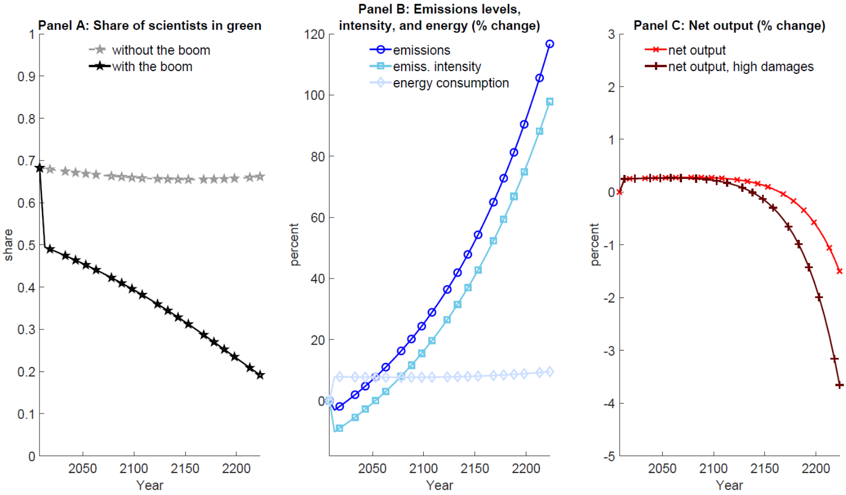


# Model

- Build a model with 3 sources of energy: coal based, natural gas based and green.
  - Natural gas pollutes less than coal.
  - Natural gas and coal both require a resource in infinite supply but costly to extract.
  - Shale gas boom: shock to the productivity of natural gas extraction.
- We show that innovation gets redirected away from green toward fossil fuel electricity.
- Calibrate to the US electricity sector.

# Laissez faire results

- Effect of one-time 50% increase in gas extraction technology:



# Some other applications

- Acemoglu, Akcigit, Hanley and Kerr (2016): merge AABH with a firm-dynamics model.
  - Calibrate the model using firm-level data from the energy sector.
  - Quantitative results confirm the role of research subsidies on top of carbon taxation.
- Fried (2018) uses the oil shocks of the 1970s to calibrate a DTC model which combines clean, dirty and energy saving innovation and then use the model to simulate climate policy.
- Stern, Pezzey and Lu (2020) explain the Industrial Revolution as resulting from the transition from wood-power to coal-power.
  - Model similar to the energy-saving vs energy-using case.
- Aghion, Barrage, Hémous and Liu (2024) model energy transition along the supply chain (different innovation model):
  - Focus on coordination issues in green innovation across different sectors;
  - Argue for sector-specific clean innovation subsidies.
- Lit review in Hémous and Olsen (2021).

# Conclusion

- Innovation is *very* endogenous and climate policies must take this into account:
- A carbon tax is not enough, subsidies to clean research are necessary;
  - but for energy-saving innovation, carbon taxes can do the heavy lifting.
- The cost of delaying intervention are large;
- A unilateral policy should focus on developing clean technologies;
- Intermediate technologies (such as natural gas) may backfire.