Carbon Taxes, Path Dependency and Directed Technical Change: Evidence from the Auto Industry


May 19, 2011
Motivation

- Providing incentives to develop new climate-friendly technologies: a focus of environmental policy
- How to induce “clean” technical change?
  - Acemoglu, Aghion, Bursztyn and Hemous (AER, forthcoming) analyse optimal environmental policy with directed technological change
  - Path-dependence in the direction of technical change leads to lock-in with dirty technologies
  - Carbon taxes + subsidies to clean R&D can redirect technical change
Questions

- Do firms respond to policies by changing direction of innovation?
  - Fuel prices
  - Subsidies to clean R&D
- How important is path-dependence in types of clean or dirty technologies?
- What type of heterogeneity in firm response to policies?
Questions

- Do firms respond to policies by changing direction of innovation?
  - Fuel prices
  - Subsidies to clean R&D
- How important is path-dependence in types of clean or dirty technologies?
- What type of heterogeneity in firm response to policies?
- Case study: auto industry
  - Contributor to greenhouse gases
  - Distinction between clean and dirty technologies
Firms invest in 2 types of R&D (clean or dirty)
- Past innovations add to the knowledge stock of firms (clean/dirty)
- Firms innovate based on accumulated knowledge stock
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If market for clean cars (e.g. electric/hybrid) is expected to grow, more incentive to invest in clean (relative to dirty)
  - Higher taxes on fuel → greater investment in “clean” research → more patents in clean
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Subsidies to clean R&D encourage clean innovation
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- Higher taxes on fuel $\rightarrow$ greater investment in “clean” research $\rightarrow$ more patents in clean

Subsidies to clean R&D encourage clean innovation

Pro-clean policy may lead to different responses by firms

- If path-dependency then clean firms will continue to do clean
- Bigger change for dirty firms
This paper

- Use firm level data on clean and dirty patenting in the automotive industry to study the response of patenting
  - To previous specialisation in either clean or dirty
  - To fuel price/tax changes
  - To clean R&D subsidies
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- Use firm level data on clean and dirty patenting in the automotive industry to study the response of patenting
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- The first paper to jointly analyze the effect of energy price and of path-dependence on innovation at the firm level
Related papers

- Popp (2002, AER) uses US patent data from 1970 to 1994 to study the effect of energy prices on energy-efficient innovations
  - only US-based innovation
  - not simultaneously analyse clean and dirty
  - not consider path dependance

- Newell, Jaffe and Stavins (1999, QJE): increased energy prices in the US led to technological improvements in energy efficiency of air conditioners and water heaters

- Country-level evidence that higher fuel price/taxes lead to increased innovation in energy-efficient automotive technology
  - Crabb & Johnson (2010), Vollebergh (2009)
Outline

- Econometric Approach
- Data & Descriptive statistics
- Regression Results
- Counterfactual scenarios
- Discussion and Conclusion
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Innovation equations: dirty

\[ PATD_{it} = \exp(\alpha^D \ln P_{it-1} + \beta^D \ln KPATD_{it-1} + \gamma^D \ln KPATC_{it-1} \\
+ \delta^D X_{it-1} + \eta_i^D + \tau_t^D + u_{it}^D) \]

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- **\( \tau_t^D \)**: time dummies
- **\( u_{it}^D \)**: random error term
Innovation equations: clean

\[
PATC_{it} = \exp(\alpha^C \ln P_{it-1} + \beta^C \ln KPATD_{it-1} + \gamma^C \ln KPATC_{it-1} \\
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Outline

- Econometric Approach
- Data & Descriptive statistics
- Regression Results
- Counterfactual scenarios
- Discussion and Conclusion
Data sources

- Data comes from the World Patent Statistical Database (PATSTAT), maintained by the European Patent Office (EPO).
- All patents filed from 1978 to 2007 at the EPO pertaining to “clean” and “dirty” technologies in the automotive industry.
  - 37,103 patents in “dirty” technologies (regular combustion engine).
  - 12,438 patents in “clean” technologies (electric vehicles, hybrid vehicles, fuel cells..).
Ratio of clean to dirty patents filed at the EPO, 1980-2007
## Identifying clean patents

<table>
<thead>
<tr>
<th>IPC code</th>
<th>Description</th>
<th>Number of patents</th>
</tr>
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<tbody>
<tr>
<td>B60K 1</td>
<td>Arrangement or mounting of electrical propulsion units</td>
<td>373</td>
</tr>
<tr>
<td>B60K 6</td>
<td>Arrangement or mounting of hybrid propulsion systems comprising electric motors and internal combustion engines</td>
<td>1378</td>
</tr>
<tr>
<td></td>
<td>Electric devices on electrically-propelled vehicles for safety purposes; Monitoring operating variables, e.g. speed, deceleration, power consumption</td>
<td></td>
</tr>
<tr>
<td>B60L 3</td>
<td>Dynamic electric regenerative braking</td>
<td>80</td>
</tr>
<tr>
<td>B60L 11</td>
<td>Electric propulsion with power supplied within the vehicle</td>
<td>951</td>
</tr>
<tr>
<td>B60L 15</td>
<td>Methods, circuits, or devices for controlling the traction-motor speed of electrically-propelled vehicles</td>
<td>354</td>
</tr>
<tr>
<td>B60R 16</td>
<td>Electric or fluid circuits specially adapted for vehicles and not otherwise provided for</td>
<td>192</td>
</tr>
<tr>
<td>B60S 5</td>
<td>Supplying batteries to, or removing batteries from, vehicles</td>
<td>25</td>
</tr>
<tr>
<td>B60W 10</td>
<td>Conjoint control of vehicle sub-units of different type or different function</td>
<td>1174</td>
</tr>
<tr>
<td>B60W 20</td>
<td>Control systems specially adapted for hybrid vehicles</td>
<td>257</td>
</tr>
<tr>
<td>H01M 8</td>
<td>Fuel cells</td>
<td>8065</td>
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## Identifying dirty patents

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<tbody>
<tr>
<td>F02B</td>
<td>Internal-combustion piston engines; combustion engines in general</td>
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<td>F02F</td>
<td>Cylinders, pistons, or casings for combustion engines; arrangement of sealings in combustion engines</td>
<td>2637</td>
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<tr>
<td>F02M</td>
<td>Supplying combustion engines with combustible mixtures or constituents thereof</td>
<td>12200</td>
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- There might be some “grey” patents
  - F02M39 to F02M71: fuel efficiency of regular combustion engine
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  - BAD!
  - Example: Peugeot / Peugeot S.A. / Peugeot Automobiles / Peugeot France etc
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- Result: 6827 distinct patent holders holding at least one clean or one dirty patent (4366 companies and 2461 individuals)
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- Result: 6827 distinct patent holders holding at least one clean or one dirty patent (4366 companies and 2461 individuals)

- For every patent holder count clean and dirty patent applications filed every year
  - $PATC_{it}$, $PATD_{it}$
  - We construct patent stocks using a 15% depreciation rate ($\delta$)
  - For clean and dirty separately: $KPATC_{it} = PATC_{it} + \delta KPATC_{it-1}$
Patents as an indicator of innovation

- **Main advantage: availability**
  - Can be disaggregated at technology level
  - Available at firm level

- **Limitations**
  - Not all inventions patented: propensity to patent differs between industries
    → Focus on a single sector
  - The value of patents is heterogeneous
    → Focus on patents filed at the EPO (quality threshold)
    → Use citation data to weight for quality (as robustness check)
Constructing firm-level fuel prices

- How to obtain variation in price?

Data on fuel prices available at the country level from IEA.

- Use French price for firm with HQ in France?

  → Global industry: firms influenced by prices in different countries.
  
  Use weighted average of all country prices where weights depend on
  where firms expect to be selling cars.

  \[ P_{it} = \sum w_{ic} P_{ct} \]

  Weights are time-constant and calculated on pre-sample period (1978-1985) to avoid endogeneity; estimate 1986-2007.
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1. The firm's patent portfolio across countries
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- Suppose that firm $i$ has 3 patents over the period 1978-1985 (in clean, dirty, and other technologies)
  - 2 patents filed in Germany and 1 in the US
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- Suppose that firm $i$ has 3 patents over the period 1978-1985 (in clean, dirty, and other technologies)
  - 2 patents filed in Germany and 1 in the US
- The firm is mostly present in Germany, but the German market is smaller than that of the US
  - Each country is weighted according to its 1978-1985 share in the world’s GDP

\[ P_{it} = P_{\text{Germany}, t} \times \text{GDP}_{\text{Germany}}/\text{GDP}_{\text{World}}^2 + P_{\text{USA}, t} \times \text{GDP}_{\text{USA}}/\text{GDP}_{\text{World}}^3 \]
Example

- Suppose that firm $i$ has 3 patents over the period 1978-1985 (in clean, dirty, and other technologies)
  - 2 patents filed in Germany and 1 in the US
- The firm is mostly present in Germany, but the German market is smaller than that of the US
  - Each country is weighted according to its 1978-1985 share in the world’s GDP
- The price variable in our regressions would become

$$P_{it} = P_{Germany,t} \times \frac{GDP_{Germany}}{GDP_{World}} \times \frac{2}{3} + P_{USA,t} \times \frac{GDP_{USA}}{GDP_{World}} \times \frac{1}{3}$$
Fuel taxes in selected countries

![Graph showing fuel taxes in selected countries](image)
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### Basic results on clean and dirty innovation (OLS)

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<thead>
<tr>
<th>Dep. Variable</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean</td>
<td>Clean</td>
<td>Dirty</td>
<td></td>
<td>Clean</td>
<td>Dirty</td>
<td></td>
</tr>
<tr>
<td>Fuel Price (including tax)</td>
<td>0.769***</td>
<td>0.570***</td>
<td>0.04</td>
<td>-0.618**</td>
<td>-0.565**</td>
<td>-0.487**</td>
</tr>
<tr>
<td>ln P_{it-1}</td>
<td>(0.184)</td>
<td>(0.165)</td>
<td>(0.148)</td>
<td>(0.250)</td>
<td>(0.228)</td>
<td>(0.197)</td>
</tr>
<tr>
<td>Stock of clean patents</td>
<td>0.214***</td>
<td>0.213***</td>
<td>-0.12</td>
<td>0.058***</td>
<td>0.058***</td>
<td>-0.06</td>
</tr>
<tr>
<td>ln(1+KPATC_{it-1})</td>
<td>(0.014)</td>
<td>(0.013)</td>
<td>(0.124)</td>
<td>(0.011)</td>
<td>(0.011)</td>
<td>(0.084)</td>
</tr>
<tr>
<td>Stock of dirty patents</td>
<td>0.035***</td>
<td>0.039***</td>
<td>0.02</td>
<td>0.113***</td>
<td>0.113***</td>
<td>0.234***</td>
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<td>ln(1+KPATD_{it-1})</td>
<td>(0.006)</td>
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<td>(0.046)</td>
<td>(0.015)</td>
<td>(0.015)</td>
<td>(0.084)</td>
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<td>Stock of clean patents X Fuel Price</td>
<td>-0.04</td>
<td>-0.02</td>
<td></td>
<td>-0.02</td>
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<td></td>
</tr>
<tr>
<td>ln(1+KPATC_{it-1}) X ln P_{it-1}</td>
<td>(0.043)</td>
<td>(0.027)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stock of dirty patents X Fuel Price</td>
<td>0.116***</td>
<td>0.01</td>
<td></td>
<td>0.01</td>
<td></td>
<td></td>
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<tr>
<td>ln(1+KPATD_{it-1}) X ln P_{it-1}</td>
<td>(0.022)</td>
<td>(0.032)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Controls for GDP &amp; GDP per capita</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
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<td>yes</td>
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<tr>
<td>Firm Fixed Effects</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Country by Year Fixed Effects</td>
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<td>yes</td>
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</tr>
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<td>Observations</td>
<td>150194</td>
<td>150194</td>
<td>150194</td>
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<tr>
<td>Firms</td>
<td>6827</td>
<td>6827</td>
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## Count data models

<table>
<thead>
<tr>
<th>Dep. Variable</th>
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<tbody>
<tr>
<td></td>
<td>Number of Patent applications</td>
<td></td>
<td>Clean</td>
<td>Dirty</td>
</tr>
<tr>
<td>Fuel Price (including tax)</td>
<td>1.239***</td>
<td>1.360***</td>
<td>-0.828***</td>
<td>-0.329***</td>
</tr>
<tr>
<td>(\ln P_{it-1})</td>
<td>(0.139)</td>
<td>(0.140)</td>
<td>(0.089)</td>
<td>(0.086)</td>
</tr>
<tr>
<td>Stock of clean patents</td>
<td>1.456***</td>
<td>1.462***</td>
<td>-0.102***</td>
<td>-0.070***</td>
</tr>
<tr>
<td>(\ln(1+KPATC_{it-1}))</td>
<td>(0.008)</td>
<td>(0.008)</td>
<td>(0.006)</td>
<td>(0.006)</td>
</tr>
<tr>
<td>Stock of dirty patents</td>
<td>-0.010*</td>
<td>-0.020**</td>
<td>1.352***</td>
<td>1.431***</td>
</tr>
<tr>
<td>(\ln(1+ KPATD_{it-1}))</td>
<td>(0.006)</td>
<td>(0.009)</td>
<td>(0.004)</td>
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<td>Controls for GDP &amp; GDP per capita</td>
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<td>Firm Fixed Effects</td>
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Robustness

Our results are robust to:

1. using the tax component of the fuel price instead of the fuel price
2. using various lags of the price
3. including other variables besides fuel price (GDP, GDP per capita, population) but weighted in the same way as fuel price
4. including country-by-year fixed effects that control for other country-level policies
5. using an alternative definition of clean patents
6. modifying the period used to calculate the weights
7. dropping individual patent holders (1/3 of the data set)
8. dropping the top 1% patent holders in terms of both, clean and dirty innovation
## Clean R&D subsidies

<table>
<thead>
<tr>
<th>Dep. Variable</th>
<th>(1)</th>
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<tbody>
<tr>
<td><strong>Number of Patent applications</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean</td>
<td>0.769***</td>
<td>0.570***</td>
<td>-0.618**</td>
<td>-0.565**</td>
</tr>
<tr>
<td>Dirty</td>
<td>0.570***</td>
<td>0.365***</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Fuel Price (including tax)</td>
<td>0.769***</td>
<td>0.570***</td>
<td>-0.618**</td>
<td>-0.565**</td>
</tr>
<tr>
<td>ln $P_{it-1}$</td>
<td>(0.184)</td>
<td>(0.165)</td>
<td>(0.250)</td>
<td>(0.228)</td>
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<tr>
<td>Clean public R&amp;D</td>
<td>0.110***</td>
<td>0.215***</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>ln $RD_{it-1}$</td>
<td>(0.039)</td>
<td>(0.052)</td>
<td>(0.053)</td>
<td>(0.065)</td>
</tr>
<tr>
<td>Stock of clean patents</td>
<td>0.214***</td>
<td>0.213***</td>
<td>0.058***</td>
<td>0.058***</td>
</tr>
<tr>
<td>ln$(1+K_{PATC_{it-1}})$</td>
<td>(0.014)</td>
<td>(0.013)</td>
<td>(0.011)</td>
<td>(0.011)</td>
</tr>
<tr>
<td>Stock of dirty patents</td>
<td>0.035***</td>
<td>0.039***</td>
<td>0.113***</td>
<td>0.113***</td>
</tr>
<tr>
<td>ln$(1+K_{PATD_{it-1}})$</td>
<td>(0.006)</td>
<td>(0.006)</td>
<td>(0.015)</td>
<td>(0.015)</td>
</tr>
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<td>no</td>
<td>yes</td>
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<td>Country by Year Fixed Effects</td>
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<td>Firms</td>
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### Including electricity price

<table>
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<tbody>
<tr>
<td>Number of Patent applications</td>
<td>Clean</td>
<td>Dirty</td>
<td>Clean</td>
<td>Dirty</td>
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<tr>
<td><strong>Fuel Price (including tax)</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$\ln P_{it-1}$</td>
<td>0.499***</td>
<td>0.448***</td>
<td>-0.709***</td>
<td>-0.663***</td>
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<td></td>
<td>(0.139)</td>
<td>(0.135)</td>
<td>(0.210)</td>
<td>(0.202)</td>
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<td><strong>Electricity price</strong></td>
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<tr>
<td>$\ln E_{it-1}$</td>
<td>-0.543*</td>
<td>-0.614**</td>
<td>-0.42</td>
<td>-0.37</td>
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<td></td>
<td>(0.299)</td>
<td>(0.301)</td>
<td>(0.313)</td>
<td>(0.315)</td>
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<tr>
<td><strong>Stock of clean patents</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$\ln(1+K\text{PATC}_{it-1})$</td>
<td>0.214***</td>
<td>0.214***</td>
<td>0.058***</td>
<td>0.060***</td>
</tr>
<tr>
<td></td>
<td>(0.014)</td>
<td>(0.014)</td>
<td>(0.011)</td>
<td>(0.011)</td>
</tr>
<tr>
<td><strong>Stock of dirty patents</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$\ln(1+K\text{PATD}_{it-1})$</td>
<td>0.035***</td>
<td>0.035***</td>
<td>0.113***</td>
<td>0.114***</td>
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<td>Controls for GDP &amp; GDP per capita</td>
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<td>Firm Fixed Effects</td>
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<td>Firms</td>
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## R&D spillovers

<table>
<thead>
<tr>
<th>Dep. Variable</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
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<tbody>
<tr>
<td></td>
<td>Clean</td>
<td>Dirty</td>
<td>Clean</td>
<td>Dirty</td>
</tr>
<tr>
<td>Fuel Price (including tax)</td>
<td>0.534***</td>
<td>0.289**</td>
<td>-0.661***</td>
<td>-0.542***</td>
</tr>
<tr>
<td>ln P_it-1</td>
<td>(0.144)</td>
<td>(0.128)</td>
<td>(0.208)</td>
<td>(0.185)</td>
</tr>
<tr>
<td>Stock of clean patents</td>
<td>0.213***</td>
<td>0.213***</td>
<td>0.058***</td>
<td>0.058***</td>
</tr>
<tr>
<td>ln(1+K_PATC_it-1)</td>
<td>(0.014)</td>
<td>(0.014)</td>
<td>(0.011)</td>
<td>(0.011)</td>
</tr>
<tr>
<td>Stock of dirty patents</td>
<td>0.035***</td>
<td>0.038***</td>
<td>0.113***</td>
<td>0.113***</td>
</tr>
<tr>
<td>ln(1+K_PATD_it-1)</td>
<td>(0.006)</td>
<td>(0.006)</td>
<td>(0.015)</td>
<td>(0.015)</td>
</tr>
<tr>
<td>Clean spillovers</td>
<td>0.010***</td>
<td>0.009***</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ln(1+K_INVC_it-1)</td>
<td>(0.002)</td>
<td>(0.002)</td>
<td>(0.002)</td>
<td>(0.002)</td>
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<tr>
<td>Dirty spillovers</td>
<td>0</td>
<td>0.003*</td>
<td>0.011***</td>
<td>0.011***</td>
</tr>
<tr>
<td>ln(1+K_INVD_it-1)</td>
<td>(0.002)</td>
<td>(0.002)</td>
<td>(0.003)</td>
<td>(0.003)</td>
</tr>
</tbody>
</table>

| Controls for GDP & GDP per capita | no | yes | no | yes |
| Firm Fixed Effects | yes | yes | yes | yes |
| Country by Year Fixed Effects | yes | yes | yes | yes |
| Observations | 150194 | 150194 | 150194 | 150194 |
| Firms | 6827 | 6827 | 6827 | 6827 |
Outline

- Econometric Approach
- Data & Descriptive statistics
- Regression Results
- Counterfactual scenarios
- Discussion and Conclusion
Counterfactual calculations

By how much do fuel prices have to increase to have more clean than dirty innovations?

![Graph showing the relationship between fuel price change and clean/dirty innovation applications.](image_url)
The additional tax effort required varies over time:

1990

- Actual
- No dirty knowledge stocks

% fuel price change

Clean over dirty patent applications
The additional tax effort required varies over time:

**1990**
- **Actual**
- **No dirty knowledge stocks**

**2007**
- **Actual**
- **No dirty knowledge stocks**

- **Clean over dirty patent applications**
- **% fuel price change**
- **Clean over dirty patent applications**
- **% fuel price change**
Outline

- Econometric Approach
- Data & Descriptive statistics
- Regression Results
- Counterfactual scenarios
- Discussion and Conclusion
Summary of Results

In line with the predictions of our model we find that:

- Firms with previous innovation in dirty are more likely to conduct further dirty innovation (and vice versa for clean).
- Spillovers from other inventors play in the same direction, implying path dependency and lock-in.
- Firms react to fuel price increases with a reduction in dirty and an increase in clean patenting.
- Price intervention can direct the path of technological innovation, with this effect being stronger for firms with previous focus on dirty technologies.
- The tax increase required to turn the economy on a clean path would be only a third if there was no previous specialisation in dirty technologies.
Summary of Results

In line with the predictions of our model we find that:

- Firms with previous innovation in dirty are more likely to conduct further dirty innovation (and vice versa for clean)

Spillovers from other inventors play in the same direction, implying path dependency and lock-in.

Firms react to fuel price increases with a reduction in dirty and an increase in clean patenting.

Price intervention can direct the path of technological innovation. This effect is stronger for firms with previous focus on dirty technologies.

The tax increase required to turn the economy on a clean path would be only a third if there was no previous specialisation in dirty technologies.
Summary of Results

In line with the predictions of our model we find that:

- Firms with previous innovation in dirty are more likely to conduct further dirty innovation (and vice versa for clean)
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Summary of Results

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- Firms with previous innovation in dirty are more likely to conduct further dirty innovation (and vice versa for clean)
  - Spillovers from other inventors play in same direction
  - This implies path dependency and lock-in

- Firms react to fuel price increases with a reduction in dirty and increase in clean patenting

- Price intervention can direct the path of technological innovation
  - This effect is stronger for firms with previous focus on dirty technologies

- The tax increase required to turn the economy on a clean path would be only a third if there was no previous specialization in dirty technologies
Summary of Results

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- Firms with previous innovation in dirty are more likely to conduct further dirty innovation (and vice versa for clean)
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  - This implies path dependency and lock-in
- Firms react to fuel price increases with a reduction in dirty and increase in clean patenting
  - Price intervention can direct the path of technological innovation
Summary of Results

In line with the predictions of our model we find that:

- Firms with previous innovation in dirty are more likely to conduct further dirty innovation (and vice versa for clean)
  - Spillovers from other inventors play in same direction
  - This implies path dependency and lock-in
- Firms react to fuel price increases with a reduction in dirty and increase in clean patenting
  - Price intervention can direct the path of technological innovation
  - This effect is stronger for firms with previous focus on dirty
Summary of Results

In line with the predictions of our model we find that:

- Firms with previous innovation in dirty are more likely to conduct further dirty innovation (and vice versa for clean)
  - Spillovers from other inventors play in same direction
  - This implies path dependency and lock-in
- Firms react to fuel price increases with a reduction in dirty and increase in clean patenting
  - Price intervention can direct the path of technological innovation
  - This effect is stronger for firms with previous focus on dirty
- The tax increase required to turn the economy on a clean path would be only a third if there was no previous specialisation in dirty technologies
Policy implications

1. Absent government intervention, firms that have innovated dirty in the past tend to get locked in the same type of innovative activities in the future.

Higher carbon taxes induce relatively more clean innovation, which magnifies the benefit of climate change policy.

Pollution taxes redirect innovation towards clean mostly where this is needed the most, namely in firms with higher stocks of dirty innovations.
Policy implications

1. Absent government intervention, firms that have innovated dirty in the past tend to get locked in the same type of innovative activities in the future.
   \[\Rightarrow\] This makes the task of climate change mitigation harder as the default option of the economy is to continue to innovate dirty.
Policy implications

1. Absent government intervention, firms that have innovated dirty in the past tend to get locked in the same type of innovative activities in the future.
   \[\implies\] This makes the task of climate change mitigation harder as the default option of the economy is to continue to innovate dirty.
   \[\implies\] This calls for early action.
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1. Absent government intervention, firms that have innovated dirty in the past tend to get locked in the same type of innovative activities in the future.
   \[\Rightarrow\] This makes the task of climate change mitigation harder as the default option of the economy is to continue to innovate dirty.
   \[\Rightarrow\] This calls for early action.

2. Higher carbon taxes induce relatively more clean innovation, which magnifies the benefit of climate change policy.
Policy implications

1. Absent government intervention, firms that have innovated dirty in the past tend to get locked in the same type of innovative activities in the future.
   ⇒ This makes the task of climate change mitigation harder as the default option of the economy is to continue to innovate dirty.
   ⇒ This calls for early action.

2. Higher carbon taxes induce relatively more clean innovation, which magnifies the benefit of climate change policy.

3. Pollution taxes redirect innovation towards clean mostly where this is needed the most, namely in firms with higher stocks of dirty innovations.
Thanks