# The CO2 Question:
# Technical Progress and the Climate Crisis

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**ECB: November 2022**

# Climate Debate

- Global overheating is increasingly at the forefront of policy concerns
  - Tight link between carbon emissions and temperature changes (Hasselmann-Manabe, NP 2021)
  - The rise of **decarbonization policies**
  - The stated objective is to reduce carbon emissions sufficiently to avoid an average temperature rise of no more than 1.5 degrees Celsius by 2050 (net neutrality)

- Active debate on how to control emissions
  - Regulatory pressure may be insufficient to control emissions
  - Transition to a green economy also requires innovation in green technology
  - Implicit assumption in the debate is that green innovation leads to decarbonization…
  - …but is this assumption validated in the data?

- **This talk:** take a global perspective on the role of green innovation in decarbonization

# The Role of Green Innovation

- Two views on the role of green innovation:
- 1) (Dominant) Green innovation fosters firm investments in green technologies and subsequent reduction in carbon footprint (e.g., Aghion et al. 2016; Cohen et al. 2022)
  - Brown firms change from carbon-intensive production to renewable production
  - Brown firms improve efficiency of their fossil fuel use
- 2) Green innovation may stimulate consumption/production (the demand for the product). An increased efficiency of technology could lead to greater use and ultimately an increase in carbon emissions

  (Jevons (1865) paradox: The CO2 Question)
- Empirical large-scale firm-level evidence on the net effect of green innovation and its drivers is very limited

# Context and Questions

Empirical Context: **Global patenting activity**

- A large sample of global firms with carbon emissions data from 81countries
- Time period: 2005-2020

- What predicts green innovation of companies?

- What is the impact of green innovation on future corporate emissions and other policies?

- Are there spillovers to other companies?

# Data

# Datasets

- We collect information on all firms (public and private) in Orbis IP Financial data, Factset, and Worldscope
  - Info on financial variables: assets, leverage, roe, capex, country of incorporation
- Merge with Orbis IP patent data
  - Info on global patents of public and private firms: USPO, JPO, and EUPO
- Firm-level data on pollution from S&P Global Trucost (Bolton and Kacperczyk, 2021)
  - Scope 1, scope 2, and scope 3 carbon emissions
    - Scope 1 greenhouse gas (GHG) emissions occur from sources that are controlled or owned by a firm
    - Scope 2 and scope 3 are indirect and are related to energy consumption and supply chain
    - Emission data of public companies
- Firm-level institutional data from Thomson Reuters, analyst data from IBES, internal governance data from Refinitiv, media data from Ravenpack

# Our Sample

- Annual frequency over the period 2005—2020
- 11,344 global firms with financial, patent (any), and emission data
  - 5,635 firms have at least one green efficiency patent registered over the time period
  - 2,815 firms have at least one brown efficiency patent registered over the time period
- # of patents of all firms is 8,574,197; avg. # per firm is 755.84; avg. # per firm and year is 64.13
- Total number of green (brown) patents of all firms is 649,775 (216,719)
- Average number of green (brown) patents per firm is 57.28 (19.10)
- Average number of green (brown) patents per firm and year is 4.88 (1.57)
- 62,273 observations with complete financial, patent, and emission data (extensive margin)
- # of firm-year observations with either of the two patents matched to Trucost is approximately 28,668 (intensive margin)

# Classification of Innovation Activity

- We consider the following three types of innovation
  - i) Green: Technologies that may substitute carbon dioxide emitting technologies for carbon dioxide-free technologies
  - ii) Brown efficiency: Technologies that improve process efficiencies of fossil fuel sources and thus reduce carbon dioxide emissions per output
  - iii) General efficiency: Technologies that improve processes efficiencies and thus reduce carbon dioxide emissions per output

- Classifications:
  - OECD
  - IPC Green Inventory
  - Fossil fuels (FF) efficiency improving classes by Lanzi et al. (2011)
  - Self classification based on Corporate Knights Clean 200

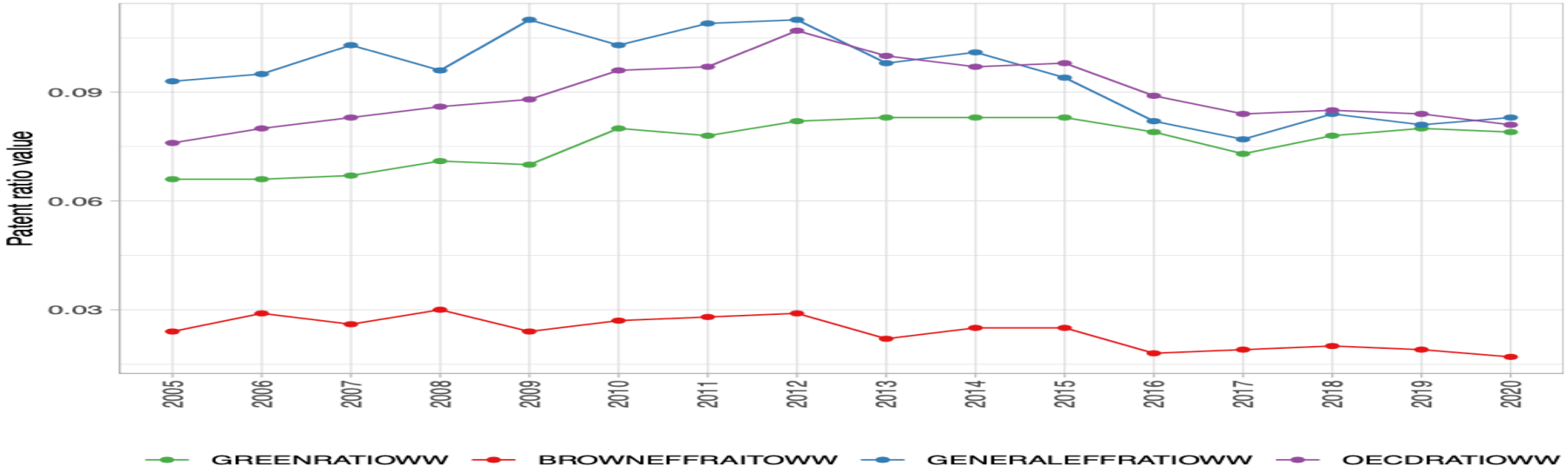
- Examples of innovation classifications:
  - Green: Wind energy
  - Green: Nuclear fusion reactors
  - Brown: Emissions abatement from stationary sources
  - Brown: Oil spill and pollutant clean-up
  - General efficiency: Energy storage
  - General efficiency: Landfilling

# Measures of Innovation Activity

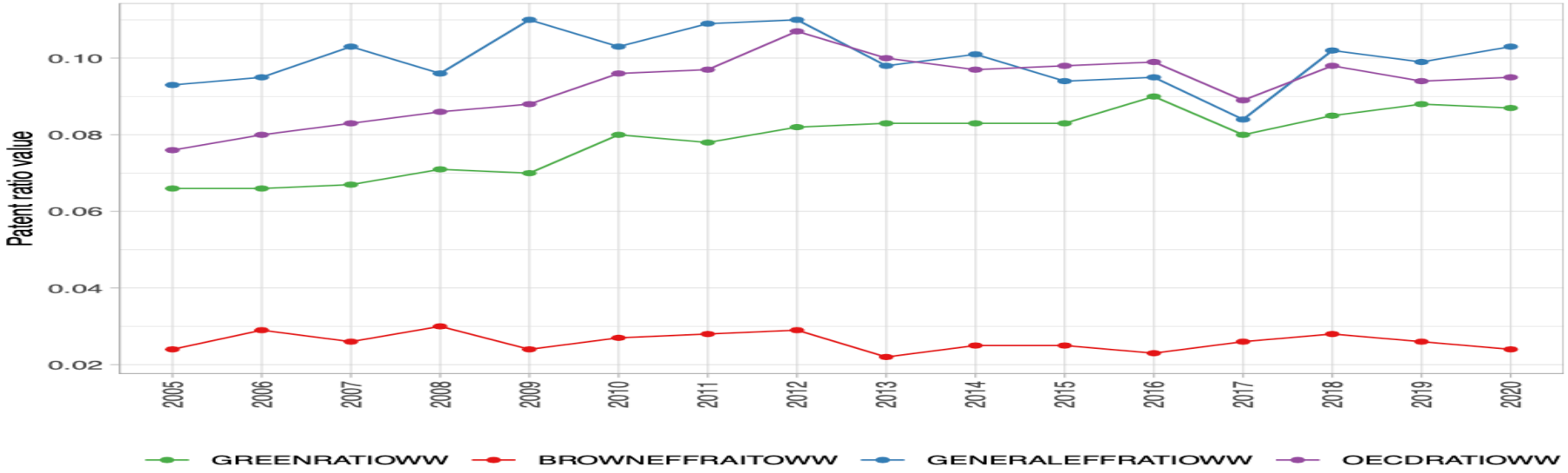
- We distinguish between worldwide (less stringent) patents and EUPO (more stringent patents)
- Results presented for EUPO
- We define measures of innovation activity
- GREENRATIOWW: green patents filed at any patent office in the world over the total number of patent filings in that year
- GREENRATIOEP: green patents filed at EUPO over the total number of patent filings in that year
- BROWNRATIOWW: brown patents filed at any patent office in the world over the total number of patent filings in that year
- BROWNRATIOEP: brown patents filed at EUPO over the total number of patent filings in that year

# Patent Ratios over Time

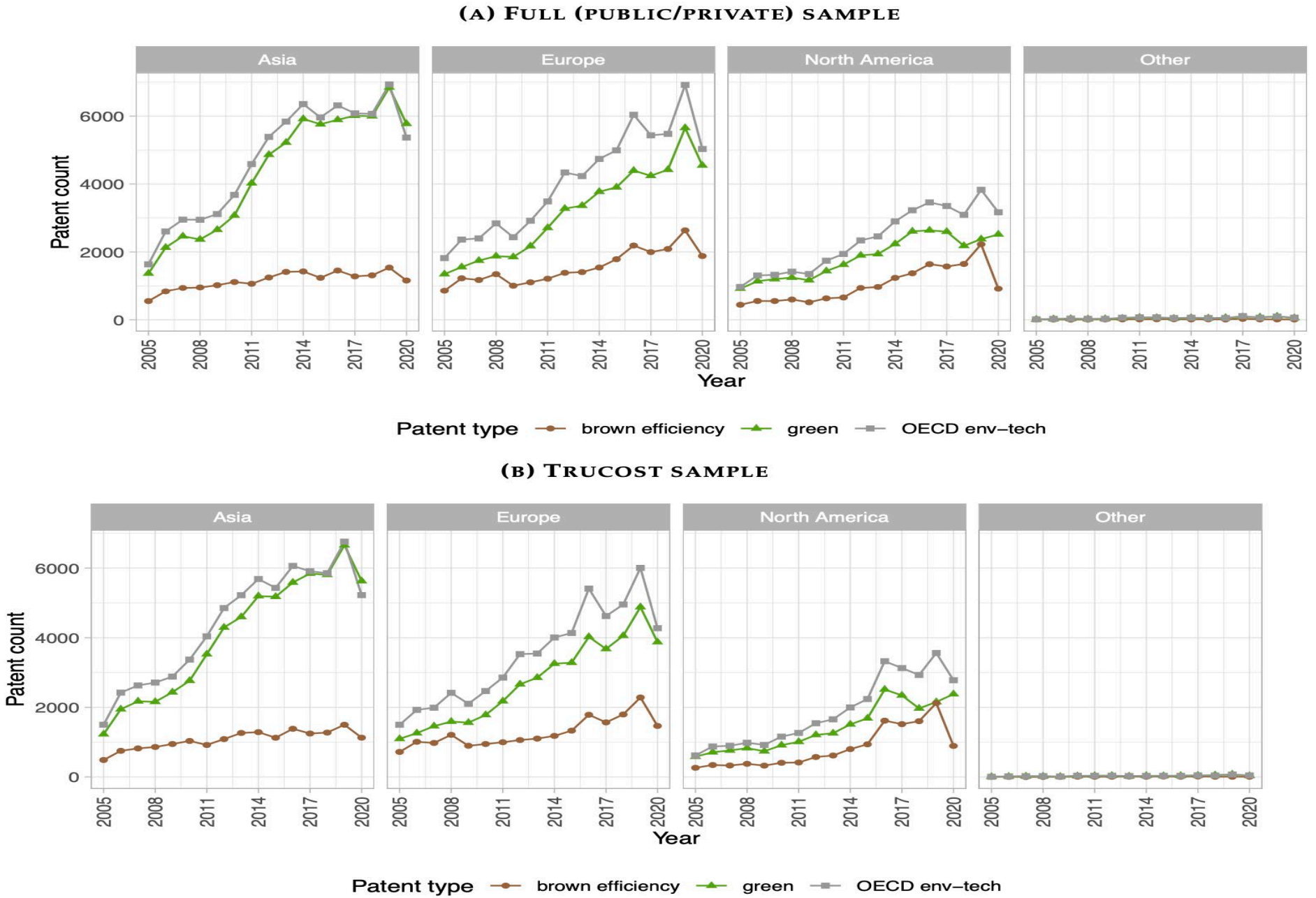
(e) Panel C.1: Annual Average Patent Ratio Full Sample




(f) Panel C.2: Annual Average Patent Ratio Legacy Sample



# Patent Ratios over Time across Regions



# Empirical Specifications

# Baseline Empirical Models: Firm-Level

- Pseudo Poisson MLE (for the extensive margin) and OLS (for the intensive margin)
- Standard errors double-clustered at firm and year dimensions

- **Baseline model 1**:

$$\text{Patent Ratio}_{f,t} = b_0 + b_1 logS1_f + \Omega Controls_f + \Gamma_c + \Gamma_{i*t} + e_{f,t}$$

- **Baseline model 2**:

$$Emissions_{f,t+h} = b_0 + b_1 \text{Patent Ratio}_{f,t} + \Omega Controls_f + \Gamma_c + \Gamma_{i*t} + e_{f,t};\ h=1,\ 3$$

- **Baseline model 3**:

$$CorpVars_{f,t+h} = b_0 + b_1 \text{Patent Ratio}_{f,t} + \Omega Controls_f + \Gamma_c + \Gamma_{i*t} + e_{f,t};\ h=1,\ 3$$

# Empirical Findings I

## *Patent Ratios*

# Do Firm Emissions and Age Affect Green Innovation?

| Panel A: Dependent variable *GREENRATIOEP* | | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| LOGS1TOT | 0.084*** | −0.029*** | 0.012 | 0.092*** | −0.051*** | 0.013 |
| | (0.005) | (0.007) | (0.014) | (0.008) | (0.011) | (0.015) |
| LOGSIZE | | | | −0.167*** | −0.094*** | 0.049** |
| | | | | (0.016) | (0.018) | (0.022) |
| Age (/100) | | | | −0.282*** | −0.171*** | |
| | | | | (0.032) | (0.030) | |
| LOGPPE | | | | 0.122*** | 0.138*** | −0.043* |
| | | | | (0.016) | (0.018) | (0.023) |
| LEVERAGE | | | | −0.006*** | −0.004*** | 0.001 |
| | | | | (0.001) | (0.001) | (0.001) |
| ROE (/100) | | | | −0.393*** | −0.171*** | −0.022 |
| | | | | (0.058) | (0.055) | (0.039) |
| M/B | | | | 0.019*** | 0.019*** | −0.004 |
| | | | | (0.006) | (0.006) | (0.005) |
| INVEST/A | | | | 0.010*** | 0.008** | 0.005* |
| | | | | (0.003) | (0.003) | (0.003) |
| BETA | | | | 0.210*** | 0.090** | −0.017 |
| | | | | (0.035) | (0.037) | (0.027) |
| VOLAT | | | | 1.996*** | 1.377*** | −0.006 |
| | | | | (0.224) | (0.235) | (0.178) |
| MOM | | | | 0.353 | −0.040 | 0.057 |
| | | | | (0.460) | (0.454) | (0.289) |
| RET | | | | −0.127 | −0.243** | 0.041 |
| | | | | (0.122) | (0.116) | (0.073) |
| MSCI | | | | 0.067** | 0.041 | 0.050 |
| | | | | (0.032) | (0.031) | (0.035) |
| Constant | 1.962*** | 3.181*** | 3.249*** | 2.311*** | 3.070*** | 3.076*** |
| | (0.039) | (0.051) | (0.104) | (0.093) | (0.094) | (0.199) |
| Country F.E. | yes | yes | yes | yes | yes | yes |
| Year F.E. | yes | yes | yes | yes | yes | yes |
| Industry F.E. | no | yes | no | no | yes | no |
| Industry X Year F.E. | no | yes | no | no | yes | no |
| Firm F.E. | no | no | yes | no | no | yes |
| Observations | 28080 | 25031 | 20173 | 27822 | 24785 | 20173 |

# Do Firm Emissions and Age Affect Brown Innovation?

Panel B: Dependent variable *BROWNEFFRATIOEP*

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| LOGS1TOT | 0.150*** | 0.066*** | −0.080*** | 0.049*** | 0.049** | −0.064** |
| | (0.008) | (0.012) | (0.030) | (0.013) | (0.020) | (0.032) |
| LOGSIZE | | | | −0.262*** | −0.056* | −0.072 |
| | | | | (0.032) | (0.031) | (0.046) |
| Age (/100) | | | | 0.259*** | 0.226*** | |
| | | | | (0.044) | (0.050) | |
| LOGPPE | | | | 0.286*** | 0.041 | −0.016 |
| | | | | (0.033) | (0.031) | (0.052) |
| LEVERAGE | | | | −0.004** | −0.000 | −0.005* |
| | | | | (0.002) | (0.002) | (0.003) |
| ROE (/100) | | | | 0.542*** | 0.218** | −0.028 |
| | | | | (0.107) | (0.098) | (0.097) |
| M/B | | | | −0.035*** | −0.022* | 0.003 |
| | | | | (0.011) | (0.011) | (0.015) |
| INVEST/A | | | | 0.000 | 0.003 | 0.006 |
| | | | | (0.007) | (0.007) | (0.008) |
| BETA | | | | 0.333*** | −0.015 | 0.033 |
| | | | | (0.062) | (0.058) | (0.047) |
| VOLAT | | | | 0.417 | 0.150 | 0.402 |
| | | | | (0.465) | (0.529) | (0.492) |
| MOM | | | | 1.268 | 0.557 | 0.535 |
| | | | | (0.905) | (0.860) | (0.657) |
| RET | | | | −0.338 | 0.062 | −0.166 |
| | | | | (0.232) | (0.236) | (0.179) |
| MSCI | | | | −0.003 | 0.102* | −0.080 |
| | | | | (0.057) | (0.053) | (0.063) |
| Constant | 0.349*** | 2.006*** | 3.547*** | 0.940*** | 2.114*** | 4.214*** |
| | (0.064) | (0.100) | (0.236) | (0.170) | (0.181) | (0.457) |
| Country F.E. | yes | yes | yes | yes | yes | yes |
| Year F.E. | yes | yes | yes | yes | yes | yes |
| Industry F.E. | no | yes | no | no | yes | no |
| Industry X Year F.E. | no | yes | no | no | yes | no |
| Firm F.E. | no | no | yes | no | no | yes |
| Observations | 27987 | 20335 | 12186 | 27729 | 20117 | 12186 |

# Innovation and Stock of Patents

| Panel A: stock since 1990 | | | | | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| | *GREENRATIOEP* | | | *BROWNEFFRATIOEP* | | |
| LOGS1TOT | 0.091*** | −0.053*** | 0.013 | 0.057*** | 0.048** | −0.064** |
| | (0.008) | (0.011) | (0.015) | (0.014) | (0.020) | (0.032) |
| PATSTOCKGREENEP (/100) | 0.051*** | 0.035*** | −0.002 | | | |
| | (0.004) | (0.004) | (0.003) | | | |
| PATSTOCKBROWNEFFEP (/100) | | | | 0.099*** | 0.046*** | −0.001 |
| | | | | (0.009) | (0.008) | (0.008) |
| Observations | 27822 | 24785 | 20173 | 27729 | 20117 | 12186 |
| R2 | | | | | | |
| Std dev dep. var. | 23.98 | 24.62 | 25.86 | 13.37 | 15.03 | 18.38 |
| Std dev LOGS1TOT | 2.670 | 2.699 | 2.584 | 2.669 | 2.761 | 2.495 |
| Eco sig LOGS1TOT | 0.0102 | 0.00577 | 0.00135 | 0.0113 | 0.00881 | 0.00871 |

# Results Summary

- Strong evidence of path dependence in the production of innovation:
  - Green firms are more likely to produce green patents; brown firms are more likely to produce brown patents
  - Young (old) firms are more likely to innovate in green (brown) sector
  - Stock of past patents predicts future patenting activity

$\Rightarrow$brown companies do not redirect their operations towards environmentally friendly activities

$\Rightarrow$they squeeze out efficiency gains in the brown industry

# Empirical Findings II

## *Real Effects*

# The Impact on Emissions and Other Corporate Decisions

- Much policy action is predicated on the assumption that technological change is the solution to the climate crisis

- **But does green/brown innovation significantly reduce carbon emissions?**
  - Green innovation may lead to more upstream emissions (e.g., solar panel and electric vehicle production require inputs and energy that cause upstream carbon emissions; the case of Tesla)
  - With brown efficiency-improving innovation the effect on carbon emission reductions may be limited because of rebound effects (e.g., fuel economy innovations for combustion engine cars may be undone by people driving longer distances; battery life improvements for cell phones may simply result in greater phone usage; the case of Iceland)

- It is unclear how much green and brown efficiency-innovation has affected direct and indirect carbon emissions

- How have companies' innovation activities changed their corporate policies, such as capital expenditures, sales, or cash holdings?

# Does Green Innovation Spur Emission Reduction?

Panel C: European Patent Office - green innovation - lag 1

| | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH |
|---|---|---|---|---|---|---|---|---|---|---|
| L1 Green Ratio EP | 0.021 | −0.019 | 0.004 | 0.019 | −0.006 | −0.009 | 0.007 | −0.047 | 0.005 | −0.027 |
| | (0.026) | (0.025) | (0.016) | (0.070) | (0.010) | (0.018) | (0.011) | (0.100) | (0.018) | (0.022) |
| Observations | 29587 | 29587 | 29586 | 29587 | 29587 | 29587 | 29587 | 29580 | 29580 | 29025 |
| R2 | 0.953 | 0.948 | 0.978 | 0.922 | 0.843 | 0.961 | 0.987 | 0.720 | 0.956 | 0.926 |
| Std. dev. dep var | 2.667 | 2.205 | 2.268 | 3.995 | 0.561 | 1.645 | 2.127 | 3.743 | 1.967 | 1.743 |
| Std. dev. patent ratio | 0.235 | 0.235 | 0.235 | 0.235 | 0.235 | 0.235 | 0.235 | 0.235 | 0.235 | 0.236 |
| Eco sig patent ratio | 0.00182 | 0.00203 | 0.000420 | 0.00112 | 0.00263 | 0.00123 | 0.000765 | 0.00296 | 0.000640 | 0.00370 |

Panel D: European Patent Office - green innovation - lag 3

| | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH |
|---|---|---|---|---|---|---|---|---|---|---|
| L3 Green Ratio EP | 0.030 | −0.005 | 0.019 | 0.075 | 0.007 | 0.018 | 0.017 | −0.397*** | −0.042* | −0.026 |
| | (0.027) | (0.028) | (0.018) | (0.072) | (0.012) | (0.018) | (0.017) | (0.114) | (0.022) | (0.023) |
| Observations | 25217 | 25217 | 25217 | 25217 | 25217 | 25217 | 25217 | 25212 | 25212 | 24764 |
| R2 | 0.956 | 0.950 | 0.976 | 0.933 | 0.861 | 0.967 | 0.978 | 0.692 | 0.947 | 0.931 |
| Std. dev. dep var | 2.661 | 2.205 | 2.241 | 3.923 | 0.569 | 1.600 | 2.134 | 3.615 | 1.980 | 1.757 |
| Std. dev. patent ratio | 0.231 | 0.231 | 0.231 | 0.231 | 0.231 | 0.231 | 0.231 | 0.231 | 0.231 | 0.232 |
| Eco sig patent ratio | 0.00265 | 0.000553 | 0.00191 | 0.00443 | 0.00277 | 0.00260 | 0.00180 | 0.0254 | 0.00487 | 0.00339 |
| Country F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Year F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Firm F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |

# Does Brown Innovation Spur Emission Reduction?

Panel C: European Patent Office - Brown Efficiency innovation - lag 1

| | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH |
|---|---|---|---|---|---|---|---|---|---|---|
| L1 Brown Eff Ratio EP | 0.031 | −0.045 | −0.014 | 0.045 | 0.008 | 0.017 | 0.005 | −0.073 | −0.014 | 0.001 |
| | (0.043) | (0.041) | (0.020) | (0.144) | (0.015) | (0.025) | (0.018) | (0.147) | (0.030) | (0.041) |
| Observations | 29587 | 29587 | 29586 | 29587 | 29587 | 29587 | 29587 | 29580 | 29580 | 29025 |
| R2 | 0.953 | 0.948 | 0.978 | 0.922 | 0.843 | 0.961 | 0.987 | 0.720 | 0.956 | 0.926 |
| Std. dev. dep var | 2.667 | 2.205 | 2.268 | 3.995 | 0.561 | 1.645 | 2.127 | 3.743 | 1.967 | 1.743 |
| Std. dev. patent ratio | 0.130 | 0.130 | 0.130 | 0.130 | 0.130 | 0.130 | 0.130 | 0.130 | 0.130 | 0.131 |
| Eco sig patent ratio | 0.00153 | 0.00265 | 0.000790 | 0.00146 | 0.00176 | 0.00137 | 0.000290 | 0.00253 | 0.000919 | 0.0000413 |

Panel D: European Patent Office - Brown Efficiency innovation - lag 3

| | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH |
|---|---|---|---|---|---|---|---|---|---|---|
| L3 Brown Eff Ratio EP | 0.080** | 0.015 | −0.003 | 0.028 | −0.008 | −0.015 | 0.003 | −0.099 | −0.009 | 0.030 |
| | (0.040) | (0.042) | (0.022) | (0.139) | (0.014) | (0.026) | (0.024) | (0.162) | (0.036) | (0.039) |
| Observations | 25217 | 25217 | 25217 | 25217 | 25217 | 25217 | 25217 | 25212 | 25212 | 24764 |
| R2 | 0.956 | 0.950 | 0.976 | 0.933 | 0.861 | 0.967 | 0.978 | 0.692 | 0.947 | 0.931 |
| Std. dev. dep var | 2.661 | 2.205 | 2.241 | 3.923 | 0.569 | 1.600 | 2.134 | 3.615 | 1.980 | 1.757 |
| Std. dev. patent ratio | 0.131 | 0.131 | 0.131 | 0.131 | 0.131 | 0.131 | 0.131 | 0.131 | 0.131 | 0.131 |
| Eco sig patent ratio | 0.00394 | 0.000900 | 0.000154 | 0.000941 | 0.00174 | 0.00122 | 0.000214 | 0.00359 | 0.000614 | 0.00222 |
| Controls F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Country F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Year F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Firm F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |

# Green Patent Citations and Future Emissions

Panel C: European Patent Office - green innovation - lag 1

| | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH |
|---|---|---|---|---|---|---|---|---|---|---|
| L1 Green Cit Ratio EP | 0.034 | 0.003 | 0.017 | −0.025 | −0.004 | −0.005 | 0.007 | −0.185** | −0.015 | −0.011 |
| | (0.024) | (0.022) | (0.014) | (0.058) | (0.009) | (0.014) | (0.010) | (0.082) | (0.016) | (0.019) |
| Observations | 28152 | 28152 | 28152 | 28152 | 28152 | 28152 | 28152 | 28145 | 28145 | 27633 |
| R2 | 0.953 | 0.947 | 0.977 | 0.923 | 0.842 | 0.960 | 0.987 | 0.726 | 0.957 | 0.925 |
| Std. dev. dep var | 2.656 | 2.190 | 2.243 | 3.973 | 0.559 | 1.636 | 2.108 | 3.706 | 1.955 | 1.733 |
| Std. dev. pat. cit. ratio | 0.260 | 0.260 | 0.260 | 0.260 | 0.260 | 0.260 | 0.260 | 0.260 | 0.260 | 0.261 |
| Eco sig pat. cit. ratio | 0.00337 | 0.000408 | 0.00201 | 0.00161 | 0.00206 | 0.000729 | 0.000863 | 0.0130 | 0.00200 | 0.00160 |

Panel D: European Patent Office - green innovation - lag 3

| | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH |
|---|---|---|---|---|---|---|---|---|---|---|
| L3 Green Cit Ratio EP | 0.011 | 0.006 | 0.017 | 0.054 | −0.000 | 0.004 | 0.021 | −0.274*** | −0.021 | −0.010 |
| | (0.024) | (0.024) | (0.015) | (0.060) | (0.010) | (0.015) | (0.015) | (0.093) | (0.019) | (0.020) |
| Observations | 24338 | 24338 | 24338 | 24338 | 24338 | 24338 | 24338 | 24333 | 24333 | 23914 |
| R2 | 0.956 | 0.949 | 0.976 | 0.932 | 0.861 | 0.967 | 0.978 | 0.694 | 0.948 | 0.931 |
| Std. dev. dep var | 2.653 | 2.197 | 2.232 | 3.896 | 0.569 | 1.593 | 2.122 | 3.602 | 1.974 | 1.749 |
| Std. dev. pat. cit. ratio | 0.258 | 0.258 | 0.258 | 0.258 | 0.258 | 0.258 | 0.258 | 0.258 | 0.258 | 0.259 |
| Eco sig pat. cit. ratio | 0.00105 | 0.000693 | 0.00191 | 0.00354 | 0.000161 | 0.000577 | 0.00259 | 0.0196 | 0.00268 | 0.00143 |
| Controls | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Country F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Year F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Firm F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |

# Brown Patent Citations and Future Emissions

Panel C: European Patent Office - Brown Efficiency innovation - lag 1

| | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH |
|---|---|---|---|---|---|---|---|---|---|---|
| L1 Brown Eff Cit Ratio EP | 0.067* | −0.020 | −0.002 | 0.133 | 0.003 | −0.012 | 0.002 | 0.022 | 0.009 | −0.007 |
| | (0.037) | (0.036) | (0.017) | (0.117) | (0.013) | (0.024) | (0.015) | (0.130) | (0.027) | (0.037) |
| Observations | 28152 | 28152 | 28152 | 28152 | 28152 | 28152 | 28152 | 28145 | 28145 | 27633 |
| R2 | 0.953 | 0.947 | 0.977 | 0.923 | 0.842 | 0.960 | 0.987 | 0.726 | 0.957 | 0.925 |
| Std. dev. dep var | 2.656 | 2.190 | 2.243 | 3.973 | 0.559 | 1.636 | 2.108 | 3.706 | 1.955 | 1.733 |
| Std. dev. pat. cit. ratio | 0.141 | 0.141 | 0.141 | 0.141 | 0.141 | 0.141 | 0.141 | 0.141 | 0.141 | 0.142 |
| Eco sig pat. cit. ratio | 0.00356 | 0.00128 | 0.000111 | 0.00472 | 0.000654 | 0.00105 | 0.000148 | 0.000832 | 0.000671 | 0.000575 |

Panel D: European Patent Office - Brown Efficiency innovation - lag 3

| | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH |
|---|---|---|---|---|---|---|---|---|---|---|
| L3 Brown Eff Cit Ratio EP | 0.036 | −0.015 | −0.011 | −0.057 | −0.010 | −0.009 | 0.002 | −0.034 | −0.006 | 0.011 |
| | (0.037) | (0.040) | (0.021) | (0.124) | (0.013) | (0.024) | (0.021) | (0.139) | (0.033) | (0.036) |
| Observations | 24338 | 24338 | 24338 | 24338 | 24338 | 24338 | 24338 | 24333 | 24333 | 23914 |
| R2 | 0.956 | 0.949 | 0.976 | 0.932 | 0.861 | 0.967 | 0.978 | 0.693 | 0.948 | 0.931 |
| Std. dev. dep var | 2.653 | 2.197 | 2.232 | 3.896 | 0.569 | 1.593 | 2.122 | 3.602 | 1.974 | 1.749 |
| Std. dev. pat. cit. ratio | 0.141 | 0.141 | 0.141 | 0.141 | 0.141 | 0.141 | 0.141 | 0.141 | 0.141 | 0.141 |
| Eco sig pat. cit. ratio | 0.00192 | 0.000991 | 0.000691 | 0.00204 | 0.00254 | 0.000836 | 0.000103 | 0.00133 | 0.000405 | 0.000902 |
| Controls | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Country F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Year F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Firm F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |

# Robustness

- All results robust to:
  - Most regions (strongest for the US and Europe)
  - Alternative industry classifications
  - Energy sector only
  - Large fraction of industries
  - Legacy sample (with emissions data pre 2016)
  - Patent count measures
  - Top quintile of patenting activity (intensity)
  - Blockbuster patents
  - Worldwide patents (weaker scrutiny)
  - Dropping firms with M&A (allocation of patents to bidders may be less clear)

# Possible Explanations of the Failure of Green Innovation

- The lack of any clear evidence of R&D activity on future carbon emissions and capital expenditure may be due to multiple reasons
  - Filing a patent may only be a first step in a protracted innovation process
  - Most patents are about incremental technological improvements that do not have a wide impact
  - When a technological breakthrough is significant it can affect multiple margins (e.g., for a brown efficiency-improving innovation the effects could be simultaneously to improve carbon efficiency and sales => overall effect on the level of emissions possibly limited)
  - Many companies are conglomerates and their R&D activity is only a small part of their operations
  - *Innovation that is patented is destined primarily to other companies and therefore would not have a significant impact on the company's carbon emissions or capital expenditures*

# Empirical Findings III

## *Industry Spillovers*

# Spillovers to Other Companies

- Innovation that is patented is destined primarily to other companies and therefore would not have a significant impact on the company's carbon emissions or capital expenditures

- Look at the effect of innovation on emissions of companies in the same industry
  - Industry-level analysis
  - Distinguish between patenting (directly affected by innovation) and non-patenting (beneficiaries of innovation) companies

# Spillovers to Other Companies: Green Patents

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Panel A: European Patent Office - green innovation - lag 1 - patenting firms | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH | LOGSALES |
| L1 GREENRATIOEP | −0.018 | 0.094 | 0.001 | −0.230 | −0.007 | −0.126** | 0.006 | −0.004 | 0.014 | 0.030 | 0.042 |
| | (0.102) | (0.102) | (0.076) | (0.286) | (0.026) | (0.052) | (0.080) | (0.244) | (0.069) | (0.064) | (0.071) |
| Observations | 4444 | 4444 | 4444 | 4444 | 4444 | 4444 | 4444 | 4444 | 4444 | 4439 | 4443 |
| R2 | 0.910 | 0.890 | 0.917 | 0.893 | 0.883 | 0.966 | 0.929 | 0.677 | 0.891 | 0.905 | 0.925 |
| Std. dev. dep var | 2.399 | 1.877 | 1.715 | 4.055 | 0.542 | 1.789 | 1.867 | 2.723 | 1.214 | 1.176 | 1.711 |
| Std. dev. patent ratio | 0.175 | 0.175 | 0.175 | 0.175 | 0.175 | 0.175 | 0.175 | 0.175 | 0.175 | 0.175 | 0.175 |
| Eco sig patent ratio | 0.00134 | 0.00875 | 0.000140 | 0.00991 | 0.00226 | 0.0124 | 0.000526 | 0.000258 | 0.00203 | 0.00440 | 0.00430 |
| Panel B: European Patent Office - green innovation - lag 3 - patenting firms | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH | LOGSALES |
| L3 GREENRATIOEP | −0.175 | −0.070 | −0.183 | −0.450 | 0.012 | −0.095 | −0.123 | −0.086 | 0.047 | 0.104 | −0.114 |
| | (0.155) | (0.149) | (0.127) | (0.321) | (0.035) | (0.063) | (0.123) | (0.268) | (0.097) | (0.076) | (0.123) |
| Observations | 3739 | 3739 | 3739 | 3739 | 3739 | 3739 | 3739 | 3739 | 3739 | 3736 | 3738 |
| R2 | 0.901 | 0.869 | 0.888 | 0.892 | 0.872 | 0.970 | 0.895 | 0.639 | 0.852 | 0.891 | 0.895 |
| Std. dev. dep var | 2.391 | 1.866 | 1.711 | 4.100 | 0.549 | 1.763 | 1.852 | 2.688 | 1.229 | 1.172 | 1.712 |
| Std. dev. patent ratio | 0.173 | 0.173 | 0.173 | 0.173 | 0.173 | 0.173 | 0.173 | 0.173 | 0.173 | 0.173 | 0.173 |
| Eco sig patent ratio | 0.0126 | 0.00651 | 0.0185 | 0.0190 | 0.00394 | 0.00934 | 0.0115 | 0.00551 | 0.00666 | 0.0153 | 0.0115 |
| Panel C: European Patent Office - green innovation - lag 1 - non-patenting firms | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH | LOGSALES |
| L1 GREENRATIOEP | −0.005 | 0.083 | 0.059 | 0.054 | 0.004 | −0.065 | 0.150* | −0.301 | 0.039 | 0.074 | 0.106 |
| | (0.094) | (0.095) | (0.081) | (0.358) | (0.028) | (0.050) | (0.082) | (0.309) | (0.067) | (0.068) | (0.080) |
| Observations | 3597 | 3597 | 3597 | 3597 | 3597 | 3597 | 3597 | 3597 | 3596 | 3595 | 3596 |
| R2 | 0.915 | 0.887 | 0.893 | 0.913 | 0.877 | 0.977 | 0.906 | 0.616 | 0.881 | 0.871 | 0.909 |
| Std. dev. dep var | 2.671 | 2.084 | 1.832 | 4.641 | 0.536 | 1.854 | 2.140 | 3.394 | 1.617 | 1.489 | 1.943 |
| Std. dev. patent ratio | 0.184 | 0.184 | 0.184 | 0.184 | 0.184 | 0.184 | 0.184 | 0.184 | 0.184 | 0.184 | 0.184 |
| Eco sig patent ratio | 0.000312 | 0.00730 | 0.00591 | 0.00215 | 0.00149 | 0.00645 | 0.0129 | 0.0164 | 0.00449 | 0.00916 | 0.0101 |
| Panel D: European Patent Office - green innovation - lag 3 - non-patenting firms | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH | LOGSALES |
| L3 GREENRATIOEP | −0.165 | 0.064 | −0.006 | 0.080 | 0.023 | 0.083* | −0.089 | −0.787** | −0.139 | 0.074 | −0.027 |
| | (0.115) | (0.115) | (0.099) | (0.245) | (0.031) | (0.046) | (0.096) | (0.325) | (0.093) | (0.077) | (0.095) |
| Observations | 2941 | 2941 | 2941 | 2941 | 2941 | 2941 | 2941 | 2941 | 2941 | 2940 | 2940 |
| R2 | 0.918 | 0.887 | 0.889 | 0.924 | 0.886 | 0.980 | 0.906 | 0.594 | 0.877 | 0.873 | 0.904 |
| Std. dev. dep var | 2.642 | 2.046 | 1.784 | 4.651 | 0.536 | 1.835 | 2.075 | 3.223 | 1.580 | 1.438 | 1.885 |
| Std. dev. patent ratio | 0.182 | 0.182 | 0.182 | 0.182 | 0.182 | 0.182 | 0.182 | 0.182 | 0.182 | 0.182 | 0.182 |
| Eco sig patent ratio | 0.0114 | 0.00570 | 0.000582 | 0.00314 | 0.00776 | 0.00827 | 0.00782 | 0.0445 | 0.0160 | 0.00935 | 0.00265 |
| Controls | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Year F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Industry F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |

# Spillovers to Other Companies: Brown Patents

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Panel A: European Patent Office - brown efficiency innovation - lag 1 - patenting firms | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH | LOGSALES |
| L1 BROWNEFFRATIOEP | −0.561** | −0.619*** | −0.341** | −0.787 | −0.108** | −0.014 | −0.249* | 0.320 | −0.112 | −0.049 | −0.303** |
| | (0.242) | (0.180) | (0.138) | (0.517) | (0.047) | (0.080) | (0.139) | (0.365) | (0.114) | (0.106) | (0.131) |
| Observations | 4444 | 4444 | 4444 | 4444 | 4444 | 4444 | 4444 | 4444 | 4444 | 4439 | 4443 |
| R2 | 0.911 | 0.890 | 0.917 | 0.893 | 0.883 | 0.966 | 0.929 | 0.677 | 0.891 | 0.905 | 0.925 |
| Std. dev. dep var | 2.399 | 1.877 | 1.715 | 4.055 | 0.542 | 1.789 | 1.867 | 2.723 | 1.214 | 1.176 | 1.711 |
| Std. dev. patent ratio | 0.106 | 0.106 | 0.106 | 0.106 | 0.106 | 0.106 | 0.106 | 0.106 | 0.106 | 0.106 | 0.106 |
| Eco sig patent ratio | 0.0247 | 0.0348 | 0.0210 | 0.0205 | 0.0209 | 0.000817 | 0.0141 | 0.0124 | 0.00977 | 0.00440 | 0.0187 |
| Panel B: European Patent Office - brown efficiency innovation - lag 3 - patenting firms | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH | LOGSALES |
| L3 BROWNEFFRATIOEP | −0.030 | −0.213 | −0.181 | 0.201 | −0.011 | −0.154* | −0.054 | 1.233*** | 0.012 | −0.056 | −0.057 |
| | (0.226) | (0.221) | (0.176) | (0.468) | (0.042) | (0.090) | (0.164) | (0.454) | (0.136) | (0.123) | (0.174) |
| Observations | 3739 | 3739 | 3739 | 3739 | 3739 | 3739 | 3739 | 3739 | 3739 | 3736 | 3738 |
| R2 | 0.901 | 0.869 | 0.888 | 0.892 | 0.872 | 0.970 | 0.895 | 0.640 | 0.852 | 0.891 | 0.895 |
| Std. dev. dep var | 2.391 | 1.866 | 1.711 | 4.100 | 0.549 | 1.763 | 1.852 | 2.688 | 1.229 | 1.172 | 1.712 |
| Std. dev. patent ratio | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 |
| Eco sig patent ratio | 0.00133 | 0.0122 | 0.0113 | 0.00525 | 0.00211 | 0.00933 | 0.00315 | 0.0491 | 0.00109 | 0.00509 | 0.00355 |
| Panel C: European Patent Office - brown efficiency innovation - lag 1 - non-patenting firms | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH | LOGSALES |
| L1 BROWNEFFRATIOEP | 0.175 | 0.034 | −0.099 | 0.679 | 0.001 | −0.074 | 0.022 | −0.144 | −0.154 | 0.088 | −0.047 |
| | (0.248) | (0.237) | (0.206) | (0.481) | (0.052) | (0.083) | (0.253) | (0.472) | (0.190) | (0.172) | (0.205) |
| Observations | 3597 | 3597 | 3597 | 3597 | 3597 | 3597 | 3597 | 3597 | 3596 | 3595 | 3596 |
| R2 | 0.915 | 0.887 | 0.893 | 0.913 | 0.877 | 0.977 | 0.906 | 0.615 | 0.881 | 0.871 | 0.909 |
| Std. dev. dep var | 2.671 | 2.084 | 1.832 | 4.641 | 0.536 | 1.854 | 2.140 | 3.394 | 1.617 | 1.489 | 1.943 |
| Std. dev. patent ratio | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 | 0.107 |
| Eco sig patent ratio | 0.00703 | 0.00177 | 0.00582 | 0.0157 | 0.000210 | 0.00430 | 0.00108 | 0.00456 | 0.0102 | 0.00638 | 0.00260 |
| Panel D: European Patent Office - brown efficiency innovation - lag 3 - non-patenting firms | LOGS1TOT | LOGS2TOT | LOGS3TOT | S1INT | S2INT | S3INT | LOGPPE | INVEST/A | LOGCAPEX | LOGCASH | LOGSALES |
| L3 BROWNEFFRATIOEP | 0.358* | 0.065 | 0.240 | 0.024 | 0.051 | −0.149 | 0.150 | 0.758 | 0.273 | 0.136 | 0.285 |
| | (0.210) | (0.221) | (0.203) | (0.409) | (0.076) | (0.096) | (0.180) | (0.623) | (0.175) | (0.131) | (0.202) |
| Observations | 2941 | 2941 | 2941 | 2941 | 2941 | 2941 | 2941 | 2941 | 2941 | 2940 | 2940 |
| R2 | 0.918 | 0.887 | 0.890 | 0.924 | 0.886 | 0.980 | 0.906 | 0.593 | 0.877 | 0.873 | 0.904 |
| Std. dev. dep var | 2.642 | 2.046 | 1.784 | 4.651 | 0.536 | 1.835 | 2.075 | 3.223 | 1.580 | 1.438 | 1.885 |
| Std. dev. patent ratio | 0.108 | 0.108 | 0.108 | 0.108 | 0.108 | 0.108 | 0.108 | 0.108 | 0.108 | 0.108 | 0.108 |
| Eco sig patent ratio | 0.0146 | 0.00346 | 0.0146 | 0.000554 | 0.0104 | 0.00879 | 0.00784 | 0.0255 | 0.0187 | 0.0103 | 0.0164 |
| Controls | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Year F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Industry F.E. | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |

# Summary: Main Results and Contribution to the Literature

- Energy revolution is frequently presented as a way to address the climate crisis
- Our evidence suggests that more green innovation does not translate into reductions in emissions => consistent with Jevons paradox
- Companies that innovate in green (brown) space tend to be green (brown) companies => consistent with path-dependency argument of Aghion et al. (2016)
- Little evidence of significant spillovers to other firms in the same industry; some evidence that brown innovators capture a greater share of the market and thus negatively affect emissions of other firms (short-run) and positively affect investments (long-run)
- **Contribution to the literature:** the first comprehensive analysis of global green/brown patents with evidence on firm-level emission impact