The CO2 Question:
Technical Progress and the Climate Crisis

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Green Innovation is the Silver Bullet?

- **Larry Fink** in 2022 letter to shareholders: “*The next 1,000 unicorns won’t be search engines or social media companies, they’ll be sustainable, scalable innovators—startups that help the world decarbonize and make the energy transition affordable for all consumers*”

News

Why Green Hydrogen Just Might Be the Silver Bullet Against Climate Change

By FuelCellsWorks | December 12, 2021 | *3 min read* (596 words)

- **Tech Billionaires Bet on Fusion as Holy Grail for Business** (WSJ 04/23/2023)

- **Bill Gates upbeat on climate innovation, even if 1.5C goal out of reach** (Reuters, 12/20/ 2022)
  - Gates has invested more than $2 billion toward climate technologies, including direct air capture, solar energy and nuclear fission. The 14-year-old fission company TerraPower, in which Gates has invested, aims to have a demo reactor running by 2030.

Two views on green innovation

1) Green innovation fosters firm investments in green technologies (R&D) and **subsequent reductions in carbon emissions** (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

2a) Green innovation may stimulate consumption/production (the demand for the product). This could lead to greater use and ultimately an **increase in carbon emissions** (Jevons (1865) paradox)

2b) Arrow: Replacement effect (1962) & Economics of Learning-by-doing (1971)

2c) Displacement effect: emissions may spill over to other parts of the production network (Tesla) or other companies (Ford => Toyota)

Questions

Coverage

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

- **Do firms switch their technological profile?**
  - Is there path dependency in green innovation? The role of learning-by-doing
  - Is there evidence of Arrow replacement effect?

- **What is the impact of green innovation on future corporate carbon emissions?**
  - Is there evidence of Jevons' paradox?

- **Are there spillovers to other companies?**
  - Is there evidence of emission displacement?

Data

Data Sets

- We collect financial 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 GHG emissions from S&P Global Trucost (Bolton and Kacperczyk, 2021)
  - Scope 1, scope 2, and scope 3 (upstream and downstream) 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

Our Sample

- Annual frequency: firm and industry level
- **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 two 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 unit of 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

Classification of Innovation Activity

(A) Unique words in "Green"

(B) Unique words in "OECD"

Patent Counts and Innovation Capacity (Scale & Scope)

Extensive margin → (1) … (6) ← Intensive margin

	(1)	(2)	(3)	(4)	(5)	(6)
		ANYCOUNTEP w. zeros			ANYCOUNTEP w/o zeros	
PATSTOCKANYEP (/100)	0.017***	0.012***	−0.002***	0.016***	0.013***	−0.002***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Age (/100)	0.150***	0.116***		0.075**	0.097***	
	(0.032)	(0.026)		(0.030)	(0.025)	
LOGSIZE	0.613***	0.266***	0.029	0.410***	0.236***	0.033
	(0.025)	(0.029)	(0.023)	(0.024)	(0.025)	(0.023)
LOGNOEMPL	0.330***	0.127***	0.050**	0.284***	0.133***	0.050**
	(0.015)	(0.021)	(0.024)	(0.017)	(0.018)	(0.024)
LOGASSETS	−0.107***	0.466***	0.193***	0.058**	0.414***	0.178***
	(0.020)	(0.054)	(0.057)	(0.023)	(0.048)	(0.058)
LOGPPE	−0.038***	−0.000	0.112**	−0.117***	−0.040	0.112**
	(0.014)	(0.035)	(0.045)	(0.019)	(0.037)	(0.045)
LEVERAGE	−0.010***	−0.004***	−0.003***	−0.008***	−0.003***	−0.003***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
ROE (/100)	−0.276***	−0.043	−0.108**	−0.178**	−0.016	−0.110**
	(0.094)	(0.082)	(0.046)	(0.079)	(0.067)	(0.046)
M/B	−0.026***	0.007	0.001	−0.013*	0.000	0.001
	(0.008)	(0.006)	(0.005)	(0.008)	(0.006)	(0.005)
INVEST/A	−0.014***	0.000	−0.001	0.003	0.007	−0.001
	(0.005)	(0.005)	(0.004)	(0.005)	(0.005)	(0.004)
BETA	0.331***	0.122***	0.028	0.261***	0.153***	0.033
	(0.037)	(0.034)	(0.022)	(0.035)	(0.032)	(0.022)
VOLAT	2.907***	1.495***	−0.321	2.311***	1.167***	−0.280
	(0.260)	(0.282)	(0.245)	(0.345)	(0.334)	(0.245)
MOM	−2.575***	−0.937*	0.221	−2.258***	−0.968*	0.190
	(0.624)	(0.561)	(0.301)	(0.582)	(0.520)	(0.302)
RET	−0.002	0.074	−0.010	−0.018	0.022	−0.001
	(0.181)	(0.139)	(0.075)	(0.164)	(0.132)	(0.075)
MSCI	0.021	0.023	0.053*	−0.015	0.012	0.042
	(0.044)	(0.032)	(0.029)	(0.040)	(0.029)	(0.029)
Constant	−4.610***	−4.549***	1.501***	−2.770***	−3.375***	1.621***
	(0.137)	(0.145)	(0.320)	(0.137)	(0.143)	(0.323)
Observations	64648	60297	36415	24496	23231	23450
Pseduo R2	0.652	0.833	0.921	0.640	0.808	0.909
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

Measures of Innovation Activity

- We distinguish between worldwide (less stringent) and EUPO (more stringent) patents

- Results presented for EUPO

- We define two main measures of innovation activity

- GREENRATIOEP: green patents filed at EUPO 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

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**:

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

- **Baseline model 2**:

$$Emissions_{\text{ f,t+h}} = b_0 + b_1 \text{Patent Ratio}_{\text{f,t}} + \Omega Controls_f + \Gamma_f + \Gamma_t + e_{f,t};\ h{=}1, 3, 5$$

- **Baseline model 3**:

$$CorpVars_{\text{ f,t+h}} = b_0 + b_1 \text{Patent Ratio}_{\text{f,t}} + \Omega Controls_f + \Gamma_f + \Gamma_t + e_{f,t};\ h{=}1, 3, 5$$

Empirical Findings I

Green Innovation and Firm Type

Firm Type and Green/Brown Innovation: Extensive Margin

	(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)
Age (/100)	−0.299***	−0.185***		0.236***	0.218***	
	(0.033)	(0.030)		(0.045)	(0.050)	
LOGSIZE	−0.190***	−0.110***	0.049**	−0.306***	−0.083***	−0.072
	(0.017)	(0.018)	(0.022)	(0.032)	(0.031)	(0.046)
LOGPPE	0.124***	0.137***	−0.043*	0.281***	0.042	−0.016
	(0.016)	(0.018)	(0.023)	(0.033)	(0.031)	(0.052)
LEVERAGE	−0.006***	−0.004***	0.001	−0.005***	−0.001	−0.005*
	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.003)
ROE (/100)	−0.370***	−0.155***	−0.022	0.559***	0.226**	−0.028
	(0.057)	(0.055)	(0.039)	(0.105)	(0.097)	(0.097)
M/B	0.021***	0.021***	−0.004	−0.029**	−0.019*	0.003
	(0.006)	(0.006)	(0.005)	(0.011)	(0.011)	(0.015)
INVEST/A	0.010***	0.008**	0.005*	−0.001	0.003	0.006
	(0.003)	(0.003)	(0.003)	(0.007)	(0.007)	(0.008)
BETA	0.203***	0.094**	−0.017	0.312***	−0.013	0.034
	(0.035)	(0.037)	(0.027)	(0.062)	(0.058)	(0.047)
VOLAT	1.930***	1.327***	−0.006	0.248	0.118	0.402
	(0.222)	(0.234)	(0.178)	(0.473)	(0.527)	(0.492)
MOM	0.458	0.048	0.057	1.406	0.713	0.535
	(0.458)	(0.454)	(0.289)	(0.904)	(0.857)	(0.657)
RET	−0.126	−0.244**	0.042	−0.328	0.052	−0.166
	(0.122)	(0.116)	(0.073)	(0.232)	(0.235)	(0.179)
MSCI	0.068**	0.042	0.050	0.030	0.121**	−0.079
	(0.032)	(0.032)	(0.035)	(0.057)	(0.053)	(0.064)
Constant	2.476***	3.200***	3.078***	1.291***	2.315***	4.214***
	(0.094)	(0.096)	(0.199)	(0.171)	(0.185)	(0.458)
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	27822	24785	20173	27729	20117	12186
Pseudo R2	0.0772	0.317	0.516	0.100	0.439	0.527

Firm Type and Green/Brown Innovation: Intensive Margin

	(1)	(2)	(3)	(4)	(5)	(6)
	GREENRATIOEP			BROWNEFFRATIOEP		
LOGS1TOT	1.571***	−1.587***	−0.291	0.376*	−0.400	−0.253
	(0.170)	(0.252)	(0.273)	(0.197)	(0.340)	(0.506)
AGE (/100)	−6.809***	−3.153***		−0.989	−0.406	
	(0.601)	(0.603)		(0.649)	(0.803)	
PATSTOCKGREENEP (/100)	0.756***	1.024***	0.477***			
	(0.091)	(0.103)	(0.072)			
PATSTOCKBROWNEFFEP (/100)				1.360***	1.101***	0.266*
				(0.140)	(0.176)	(0.140)
Country F.E.	yes	yes	yes	yes	yes	yes
Year F.E.	yes	yes	yes	yes	yes	yes
Industry X Year F.E.	no	yes	no	no	yes	no
Firm F.E.	no	no	yes	no	no	yes
Observations	12187	10957	11352	5550	4550	5114
R2	0.220	0.534	0.815	0.187	0.526	0.762

Firm Type and Green/Brown Innovation: Emission Types

Panel A: Dependent variable *GREENRATIOEP*							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
LOGS2TOT	−0.056***						
	(0.012)						
LOGS3UPTOT		−0.128***					
		(0.018)					
LOGS3DOWNTOT			−0.025**				
			(0.010)				
S1INT (/100)				0.018			
				(0.335)			
S2INT					0.021		
					(0.025)		
S3UPINT						−0.036*	
						(0.018)	
S3DOWNINT							0.005***
							(0.002)
AGE (/100)	−0.189***	−0.176***	−0.186***	−0.195***	−0.194***	−0.194***	−0.193***
	(0.031)	(0.031)	(0.059)	(0.031)	(0.031)	(0.031)	(0.059)
PATSTOCKGREENEP (/100)	0.036***	0.035***	0.031***	0.035***	0.035***	0.034***	0.031***
	(0.004)	(0.004)	(0.006)	(0.004)	(0.004)	(0.004)	(0.006)
Controls	yes	yes	yes	yes	yes	yes	yes
Country F.E.	yes	yes	yes	yes	yes	yes	yes
Industry-Year F.E.	yes	yes	yes	yes	yes	yes	yes
Observations	24818	24818	7681	24818	24818	24818	7681
Pseudo R2	0.317	0.319	0.269	0.316	0.316	0.316	0.270

Panel B: Dependent variable *BROWNEFFRATIOEP*							
LOGS2TOT	−0.031						
	(0.023)						
LOGS3UPTOT		0.149***					
		(0.031)					
LOGS3DOWNTOT			0.005				
			(0.023)				
S1INT				0.017***			
				(0.006)			
S2INT					−0.130**		
					(0.053)		
S3UPINT						0.139***	
						(0.028)	
S3DOWNINT							0.001
							(0.003)
AGE (/100)	0.217***	0.204***	0.301***	0.215***	0.213***	0.215***	0.304***
	(0.050)	(0.050)	(0.098)	(0.050)	(0.050)	(0.050)	(0.098)
PATSTOCKBROWNEFFEP (/100)	0.048***	0.047***	0.058***	0.047***	0.047***	0.049***	0.058***
	(0.008)	(0.008)	(0.015)	(0.008)	(0.008)	(0.008)	(0.015)
Controls	yes	yes	yes	yes	yes	yes	yes
Country F.E.	yes	yes	yes	yes	yes	yes	yes
Industry-Year F.E.	yes	yes	yes	yes	yes	yes	yes
Observations	20143	20143	6426	20143	20143	20143	6426
Pseudo R2	0.439	0.440	0.420	0.439	0.439	0.440	0.420

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

⇒ **brown companies do not redirect their operations towards environmentally friendly activities**

⇒ they squeeze out efficiency gains in the brown industry

Empirical Findings II
Real Effects

The Impact of Green R&D on Future GHG Emissions

- **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)
  - **Iceland**: Produces all its electricity from renewables (geothermal energy) yet it has high carbon emissions (per capita). *How is this possible?* Because it has attracted heavy industry (aluminum plants) that comes to Iceland because of the cheap energy. This industry emits a lot of CO2!

- 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/Brown Innovation Spur Emission Reductions?

	(1) LOGS1TOT	(2) LOGS2TOT	(3) LOGS3UPTOT	(4) LOGS3DOWNTOT	(5) LOGS123UPTOT	(6) S1INT	(7) S2INT	(8) S3UPINT	(9) S3DOWNINT	(10) INVEST/A	(11) LOGCAPEX	(12) LOGSALES
Panel A: Green innovation												
L1 GREENRATIOEP	0.021	−0.019	0.007	−0.046	0.004	0.019	−0.006	−0.009	−0.018	−0.048	−0.011	0.003
	(0.026)	(0.025)	(0.015)	(0.077)	(0.015)	(0.070)	(0.010)	(0.018)	(0.389)	(0.100)	(0.014)	(0.012)
Observations	29585	29585	29584	10349	29585	29585	29585	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
R2	0.953	0.948	0.980	0.931	0.981	0.922	0.843	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
L3 GREENRATIOEP	0.002	−0.042*	0.000	0.032	−0.002	0.048	−0.000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	(0.026)	(0.025)	(0.014)	(0.118)	(0.014)	(0.070)	(0.010)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Observations	22261	22261	22261	4160	22261	22261	22261	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
R2	0.967	0.962	0.986	0.982	0.986	0.955	0.902	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
L5 GREENRATIOEP	0.015	−0.036	0.009		0.013	0.125*	0.004	[illegible]		[illegible]	[illegible]	[illegible]
	(0.028)	(0.026)	(0.017)		(0.017)	(0.069)	(0.010)	(0.018)		(0.079)	(0.013)	(0.013)
Observations	15482	15482	15482		15482	15482	15482	15482		18347	18347	18343
R2	0.973	0.965	0.985		0.986	0.972	0.933	0.981		0.888	0.956	0.989
L1 3YEARAVGGREENRATIOEP	0.007	−0.039	0.005	−0.157	−0.004	0.001	−0.003	0.002	0.079	−0.156	−0.004	−0.014
	(0.029)	(0.031)	(0.016)	(0.127)	(0.017)	(0.092)	(0.014)	(0.021)	(0.607)	(0.116)	(0.016)	(0.013)
Observations	38221	38221	38220	14552	38221	38221	38221	38221	14552	38210	38210	38214
R2	0.958	0.951	0.982	0.935	0.982	0.928	0.847	0.965	0.907	0.718	0.923	0.980
Panel B: Brown efficiency innovation												
L1 BROWNEFFRATIOEP	0.031	−0.045	−0.015	−0.241	−0.012	0.044	0.008	0.017	0.392	−0.072	0.007	−0.012
	(0.043)	(0.041)	(0.020)	(0.167)	(0.022)	(0.144)	(0.015)	(0.025)	(0.968)	(0.147)	(0.021)	(0.018)
Observations	29585	29585	[illegible]	[illegible]	[illegible]	29585	29585	[illegible]	[illegible]	[illegible]	[illegible]	29580
R2	0.953	0.948	[illegible]	[illegible]	[illegible]	0.922	0.843	[illegible]	[illegible]	[illegible]	[illegible]	0.980
L3 BROWNEFFRATIOEP	0.051	−0.001	[illegible]	[illegible]	[illegible]	−0.095	0.003	[illegible]	[illegible]	[illegible]	[illegible]	0.006
	(0.037)	(0.038)	[illegible]	[illegible]	[illegible]	(0.135)	(0.013	[illegible]	[illegible]	[illegible]	[illegible]	(0.016)
Observations	22261	22261	[illegible]	[illegible]	[illegible]	22261	22261	[illegible]	[illegible]	[illegible]	[illegible]	25155
R2	0.967	0.962	[illegible]	[illegible]	[illegible]	0.955	0.902	[illegible]	[illegible]	[illegible]	[illegible]	0.986
L5 BROWNEFFRATIOEP	0.065*	0.010	0.022		0.020	−0.067	−0.019*	0.004		0.170	0.025	0.029*
	(0.036)	(0.034)	(0.020)		(0.021)	(0.131)	(0.011)	(0.022)		(0.130)	(0.017)	(0.017)
Observations	15482	15482	15482		15482	15482	15482	15482		18347	18347	18343
R2	0.973	0.965	0.985		0.986	0.971	0.933	0.981		0.888	0.956	0.989
L1 3YEARAVGBROWNEFFRATIOEP	0.151***	−0.027	0.012	−0.136	0.028	0.095	0.004	0.024	−1.373	−0.014	−0.005	0.025
	(0.049)	(0.049)	(0.024)	(0.223)	(0.027)	(0.190)	(0.018)	(0.031)	(1.354)	(0.224)	(0.024)	(0.023)
Observations	38221	38221	38220	14552	38221	38221	38221	38221	14552	38210	38210	38214
R2	0.958	0.951	0.982	0.935	0.982	0.928	0.847	0.965	0.907	0.718	0.923	0.980
Controls	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Country F.E.	yes	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	yes
Firm F.E.	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes

Green innovation has not resulted in significant carbon emission reductions for innovating firms even after 5 years since filing the patent

brown efficiency innovations result in increased future emissions

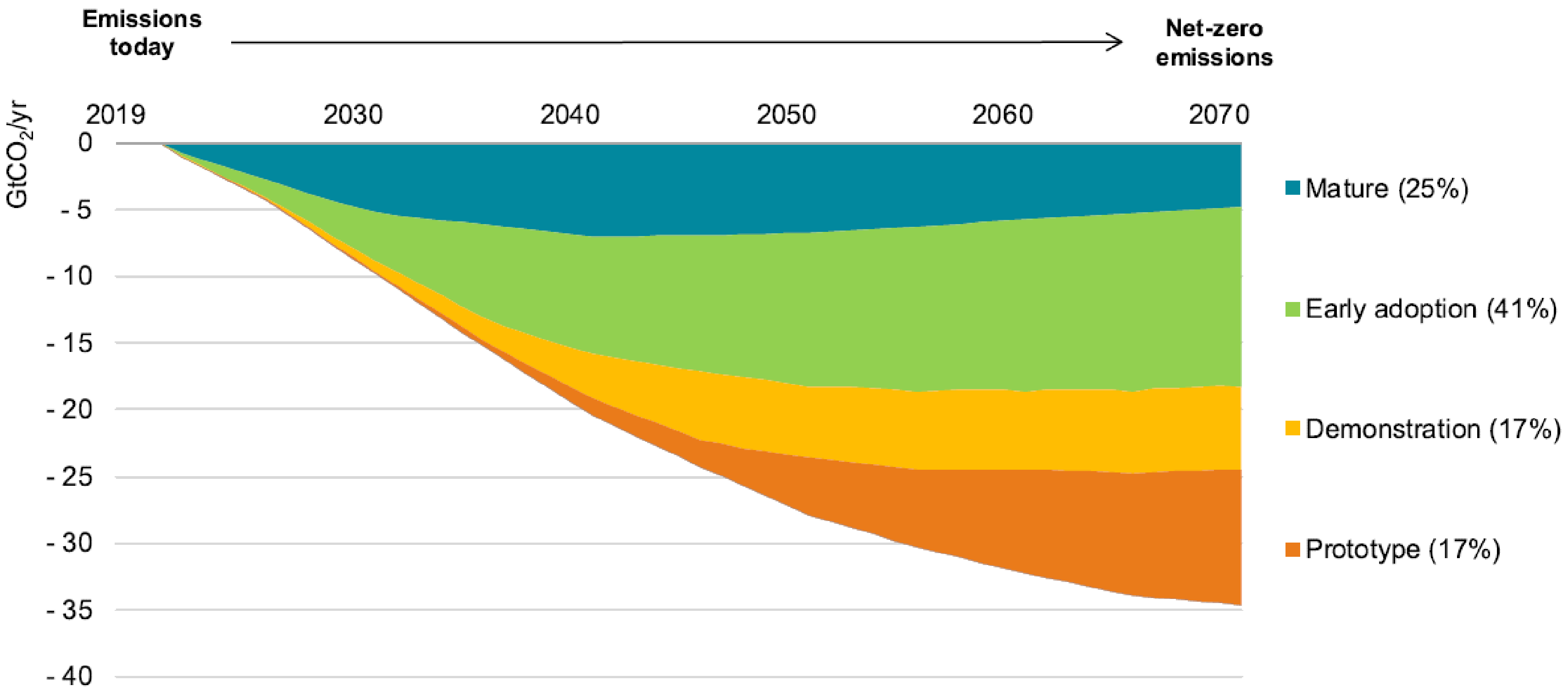
a small improvement in scope 2 emission intensity undone by an increase in sales

Possible explanations for the limited effect of green innovation

- The lack of any clear impact 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*

Renewable Energy Technological Progress

Figure 3.1 Global energy sector CO_2 emissions reductions by current technology readiness category in the Sustainable Development Scenario relative to the Stated Policies Scenario



Empirical Findings III

Industry Spillovers

Effects on Other Companies

- **Hypothesis:** Innovation that is patented is destined primarily to other companies and therefore would not have a significant impact on the company's own carbon emissions or capital expenditures, but will have effects on other companies adopting the innovation

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

Spillovers to Other Companies: **Green** Patents (Patenting/Non-Patenting Firms)

- Effects on **all** firms within the same industry:
  - green innovation is **positively** associated with future scope 1 emissions in the same industry (driven by an increase in industry sales, as scope 1 emission-intensity is reduced)
  - green innovation is associated with **higher** future scope 2 emissions, consistent with the **displacement effect**

  (e.g., 91% of electricity in West Virginia, 75% in Missouri , 74% in Wyoming and 71% in Kentucky produced with coal-fired power plants)
  - green innovation is associated with significant upstream carbon emission-intensity improvements

- Effects on **all innovating** firms in the industry:
  - no effect of green innovation on subsequent carbon emission reductions
  - green innovation is associated with higher scope 2 emissions

- Effects on **all non-innovating** firms in the industry:
  - no evidence of any within-industry spillovers between green innovators and non-innovators
  - green innovation is associated with higher scope 2 emissions and scope 2 intensity of non-innovating firms

Spillovers to Other Companies: **Brown** Patents (Patenting/Non-Patenting Firms)

- Effects on **all** firms within the same industry:
  - we find some (statistically insignificant) reduction in direct or indirect carbon emissions following greater brown patenting activity

- Effects on **all innovating** firms in the industry:
  - emissions of innovating firms increase slightly

- Effects on **all non-innovating** firms in the industry:
  - emissions (both direct and indirect) are lower
  - this effect is driven by a reduction in sales and investments

Adoption by **Other Industries**: (Patenting/Non-Patenting Firms)

Green Patents:

- Effects on **all** firms:
  - we find a significant cross-industry spillover effect on carbon emissions for upstream scope 3 emissions and for downstream scope 3 emissions (for green innovation activity averaged over three years 3YEARAVGGREENRATIOEP)
- This effect works entirely through **innovating** firms

Brown Patents

- We find a significant positive cross-industry effect on the level of downstream scope 3 emissions
- We also find a significant worsening of the scope 1 and scope 2 carbon intensity of innovating firms
- An efficiency gain in brown technology in one sector can result in increased carbon emissions in another sector (through the supply chain) by inducing greater use of a complementary brown technology.

Spillovers from the universe of privately held companies

Green Patents:

- Effects on **all** firms:
  - neither public nor private innovation is associated with any statistically significant reduction in industry-level emissions
  - We find a stronger positive association of public innovation with future scope 2 emissions; this is mostly driven by the subset of innovating companies, which are also the ones with the highest sales growth

Brown Patents

- We find that public and private innovation do not seem to have markedly different impacts on future industry-level emissions

Innovation and Market Shares

	(1)	(2)	(3)	(4)	(5)	(6)
	MKTSHR GICS6					
Panel A: Country and Industry-Year Fixed Effects						
L1 GREENRATIOEP	−0.076***					
	(0.028)					
L3 GREENRATIOEP		−0.070**				
		(0.032)				
L5 GREENRATIOEP			−0.122***			
			(0.043)			
L1 BROWNEFFRATIOEP				0.034		
				(0.049)		
L3 BROWNEFFRATIOEP					0.028	
					(0.053)	
L5 BROWNEFFRATIOEP						−0.010
						(0.067)
Observations	44202	34043	25036	44202	34043	25036
R2	0.462	0.469	0.477	0.461	0.469	0.477
Controls	yes	yes	yes	yes	yes	yes
Country F.E.	yes	yes	yes	yes	yes	yes
GICS6-Year F.E.	yes	yes	yes	yes	yes	yes
Panel B: Firm and Year Fixed Effects						
L1 GREENRATIOEP	−0.025					
	(0.021)					
L3 GREENRATIOEP		−0.046*				
		(0.025)				
L5 GREENRATIOEP			−0.042			
			(0.029)			
L1 BROWNEFFRATIOEP				0.017		
				(0.042)		
L3 BROWNEFFRATIOEP					0.040	
					(0.037)	
L5 BROWNEFFRATIOEP						−0.012
						(0.046)
Observations	43346	33147	24189	43346	33147	24189
R2	0.869	0.887	0.903	0.869	0.887	0.903
Controls	yes	yes	yes	yes	yes	yes
Year F.E.	yes	yes	yes	yes	yes	yes
Firm F.E.	yes	yes	yes	yes	yes	yes

How large is the effect of green innovation?

Panel A: Green innovation	(1) LOGS1TOT	(2) LOGS2TOT	(3) LOGS3UPTOT	(4) LOGS3DOWNTOT	(5) LOGS123UPTOT	(6) S1INT	(7) S2INT	(8) S3UPINT	(9) S3DOWNINT
L1 GREENRATIOEP	0.514***	−0.199***	−0.059**	0.153	0.111***	1.385***	0.042***	0.146***	4.168***
	(0.041)	(0.033)	(0.029)	(0.097)	(0.028)	(0.128)	(0.013)	(0.036)	(0.610)
Partial R2	0.00596	0.00167	0.000172	0.000219	0.000628	0.00760	0.000378	0.000552	0.00579
R2 Full Model	0.668	0.742	0.785	0.459	0.810	0.149	0.171	0.226	0.106
R2 Reduced Model	0.666	0.742	0.785	0.459	0.809	0.143	0.171	0.225	0.101
Observations	31049	31049	31048	11600	31049	31049	31049	31049	11600
L3 GREENRATIOEP	0.592***	−0.199***	−0.022	0.172	0.172***	1.553***	0.040**	0.145***	4.720***
	(0.048)	(0.039)	(0.034)	(0.145)	(0.032)	(0.157)	(0.016)	(0.043)	(0.956)
Partial R2	0.00748	0.00163	0.0000243	0.000293	0.00151	0.00868	0.000320	0.000518	0.00712
R2 Full Model	0.659	0.731	0.765	0.493	0.795	0.159	0.187	0.218	0.113
R2 Reduced Model	0.656	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.186	0.217	0.106
Observations	23485	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	23485	23485	5428
L5 GREENRATIOEP	0.695***	[illegible]	[illegible]		[illegible]	[illegible]	0.009	0.146***	
	(0.060)	[illegible]	[illegible]		[illegible]	[illegible]	(0.019)	(0.054)	
Partial R2	0.00954	[illegible]	[illegible]		[illegible]	[illegible]	0.0000167	0.000484	
R2 Full Model	0.635	[illegible]	[illegible]		[illegible]	[illegible]	0.196	0.209	
R2 Reduced Model	0.631	[illegible]	[illegible]		[illegible]	[illegible]	0.196	0.209	
Observations	16892	16892	16892		16892	16892	16892	16892	
L1 3YEARAVGGREENRATIOEP	0.552***	−0.226***	−0.069**	0.239***	0.129***	1.561***	0.057***	0.185***	5.290***
	(0.038)	(0.032)	(0.027)	(0.091)	(0.027)	(0.126)	(0.013)	(0.035)	(0.603)
Partial R2	0.00620	0.00192	0.000205	0.000480	0.000748	0.00836	0.000626	0.000793	0.00808
R2 Full Model	0.670	0.740	0.782	0.460	0.807	0.150	0.168	0.214	0.111
R2 Reduced Model	0.668	0.739	0.782	0.460	0.807	0.143	0.167	0.213	0.104
Observations	38934	38934	38933	15245	38934	38934	38934	38934	15245

The partial R2s typically do not exceed 1%
=>
Corporate decarbonization is explained only to a very limited extent by green R&D

Controls include: LOGSIZE, LOGPPE, LEVERAGE, ROE, M/B, INVEST/A, BETA, VOLAT, MOM, RET and MSCI

Summary: Main Results and Contribution to the Literature

- Companies that do green (brown) innovation tend to be green (brown) companies

  => path-dependency (Aghion et al., 2016) and Arrow replacement effect (replacement effect goes beyond firm operations and extends to production network)

- Companies do not switch their innovation profile even if they change their carbon profile

- More green innovation does not translate into reductions in emissions

  ⇒ consistent with Jevons' paradox

  ⇒ consistent with displacement effect

- **Implications for policies** that support blanket subsidies of green innovation; carbon problem requires coordination of efforts across companies and sectors (role for the public sector)
- We need a **green industrial policy** to overcome ecosystem replacement effects