Climate Change, Directed Innovation and Energy Transition: The Long-run Consequences of the Shale Gas Revolution

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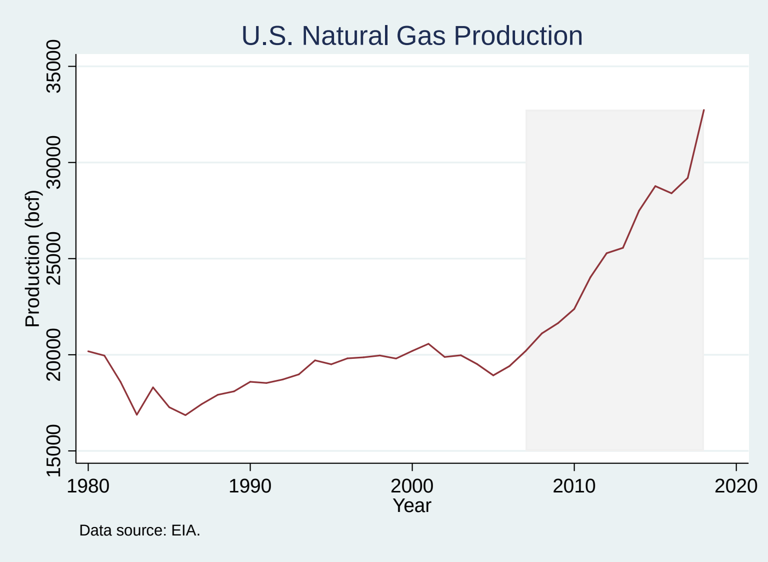
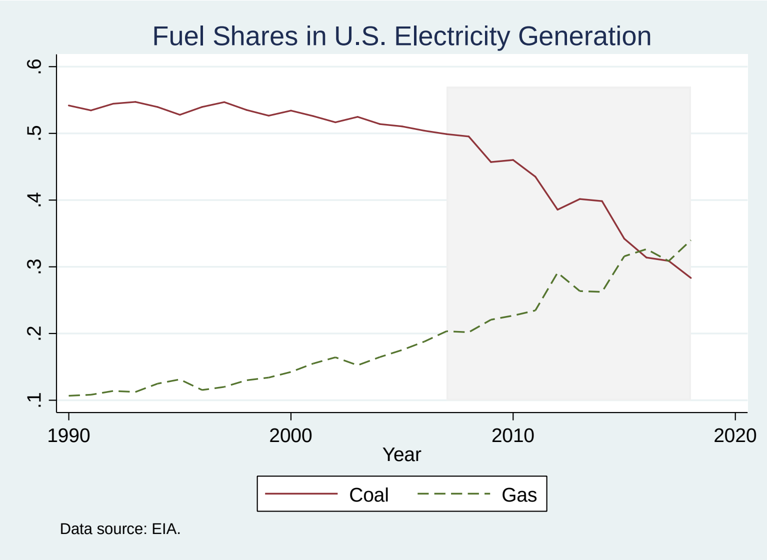
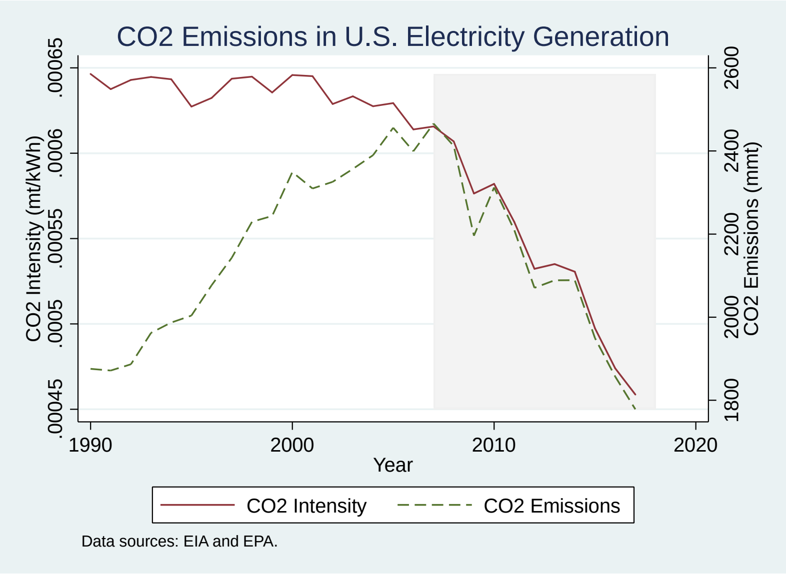
U.S. Shale Gas Revolution



The Rise of Gas



Emissions and Emissions Intensity



This Paper: Shale Impacts on Innovation, Long-Run

This Paper: Shale Impacts on Innovation, Long-Run

1. Empirically document decline in green / fossil electricity innovation

2. Theoretically analyze boom in directed technical change model:
   - ↓ CO_2 in short-run if gas sufficiently clean compared to coal
   - ↓ Green innovation at $t = 1$, for all $t \geq 1$ under suitable conditions
   - Can increase long-run emissions through several scenarios

3. Quantify shale boom, policy impacts in calibrated U.S. economy
   - Boom *increases* emissions in the long-run
   - Boom calls for stronger climate policy
     ↑ clean research subsidies, carbon price (weakly)

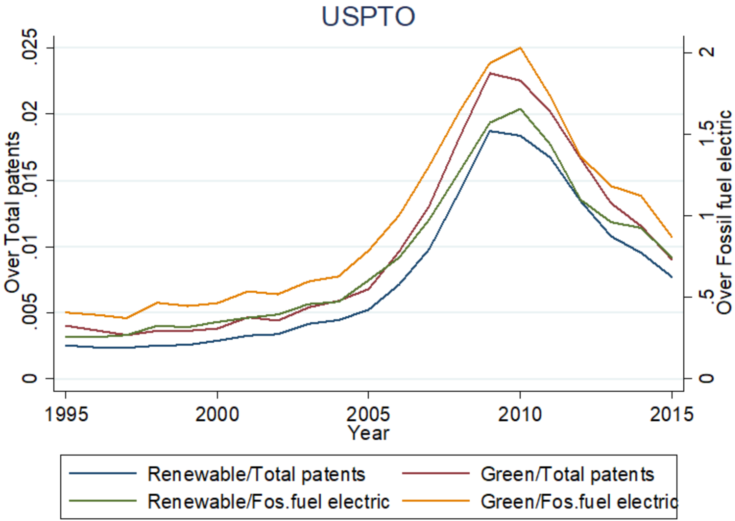
Literature Context

- IAMs: Nordhaus (1980 ... 2019); Anthoff, Tol (e.g., 2014), Hope (2011), etc.
  - Macro Effects: Golosov et al. (2014), Hassler, Krusell, Smith (2016), etc.
- Endogenous technical change IAMs: Goulder, Mathai (2000), Nordhaus (2002), Popp (2004); Bosetti et al. (2007), Bretschger et al. (2017), etc.
- Directed technical change IAMs: Acemoglu et al. (2012 "AABH", 2016), Hémous (2016), Fried (2018), Lemoine (2018), Casey (2019), etc.
  - AABH '12: path dependence in clean versus dirty innovation; optimal policy relies on carbon tax *and* clean research subsidies
- ETC Empirical evidence: Newell, Jaffe and Stavins (1999), Popp (2002), Calel and Dechezleprêtre (2012), Aghion et al. (2016), Meng (2019)
- CGE Energy Sector models: Manne (1977) ... Goulder, Hafstead (2013)
  - Shale boom simulations: Burtraw et al. (2012), Venkatesh et al. (2012), Brown and Krupnick (2010), McJeon et al. (2014)
- Empirical shale boom electricity studies: Linn, Muehlenbachs (2018), Fell, Kaffine (2018), Cullen, Mansur (2017), Holladay, LaRiviere (2017), Knittel, Metaxoglou, Trinade (2015)

Roadmap

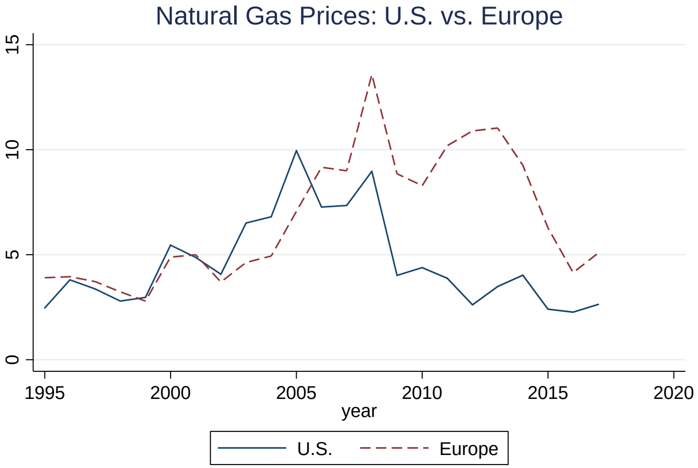
1. **Empirical Motivation**
2. Analytic Model
3. Quantitative Model
4. Conclusion

Empirical Motivation



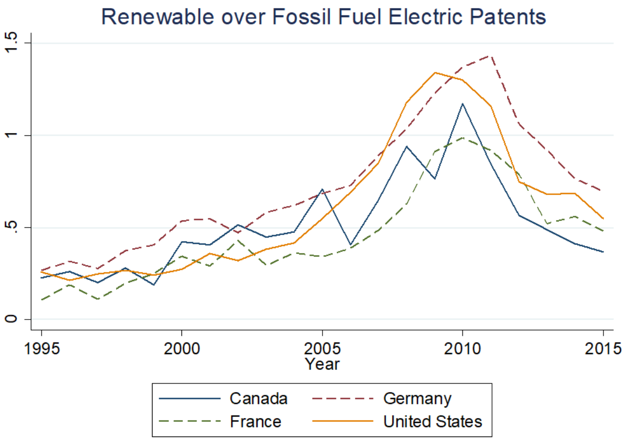
Data

Empirical Motivation



Data sources: World Bank, BLS. Real $2010.

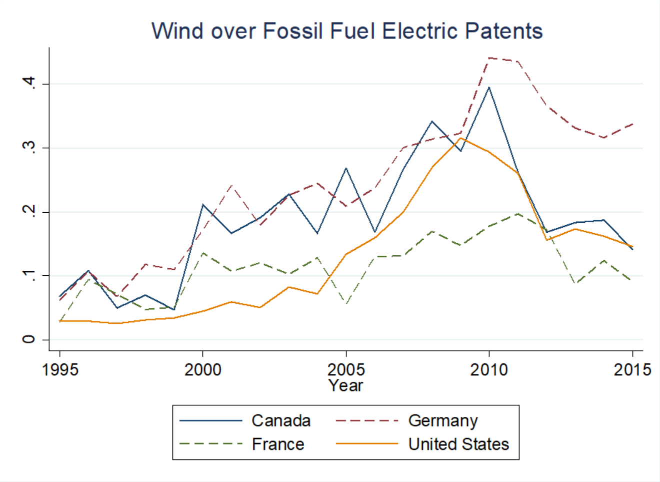
Renewables over fossil fuel patents



- Domestic patents by patent offices

Green | all | Renewable / Total Patents | Fossil fuel / Total Patents | Gov RD | Citations

Wind / Fossil Fuel



solar storage Energy saving

Price regressions

- Panel regression of patenting over natural gas prices with 2-yr lag
  - Period 1978-2015.
- Data:
  - Natural gas price indexes by country: International Energy Agency
  - GDP per capita: OECD
  - Public R&D support for fossil vs. green: International Energy Agency
- Country fixed effects; Year fixed effects

Natural Gas Prices

	Patent Office: All							
	Renewable/Fossil fuel electric				Green/Fossil fuel electric			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Panel A: log (Renewable / Fossil fuel electric)							
ln(Gas Price Index)	0.345**	0.299**	0.302**	0.318**	0.295*	0.308**	0.311**	0.318**
	(0.143)	(0.117)	(0.119)	(0.124)	(0.157)	(0.124)	(0.126)	(0.123)
ln(GDP/cap.)		1.020***	1.017***	0.327		0.894**	0.891**	0.585
		(0.342)	(0.340)	(0.785)		(0.318)	(0.324)	(0.831)
ln(Public R&D Fossil)			0.011	0.017			0.019	0.022
			(0.072)	(0.073)			(0.070)	(0.071)
ln(Public R&D Green)			0.023	-0.009			0.026	0.012
			(0.038)	(0.058)			(0.029)	(0.046)
ln(Energy consumption)				0.629				0.279
				(0.535)				(0.515)
Obs.	346	340	340	340	347	340	340	340
Countries	15	15	15	15	15	15	15	15
Adj. R^2	0.831	0.833	0.832	0.833	0.768	0.806	0.805	0.805

Note: Independent variable and controls lagged 2 periods, star levels: * 0.10, ** 0.05, *** 0.010. All regressions include country and year fixed effects. Standard errors are clustered at the country-level. Includes: AU, BE, CA, CH, CZ, DE, FR, GB, GR, JP, KR, MX, NZ, SK, US.

Granted | Weights | Domestic | Diff-in-diff | Pre-2005 Sample | Tax Controls

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Production: 3 types of energy

- Discrete time economy.
- Final good produced according to:

$$Y_t = \left((1-\nu)\, Y_{Pt}^{\frac{\lambda-1}{\lambda}} + \nu \left(\widetilde{A}_{Et} E_t \right)^{\frac{\lambda-1}{\lambda}} \right)^{\frac{\lambda}{\lambda-1}},$$

  - Y_{Pt} $\sim$ production input produced via $Y_{Pt} = A_{Pt} L_{Pt}$
  - A_{Pt}, $\widetilde{A}_{Et}$ $\sim$ productivity in goods production, energy efficiency

- Energy composite E_t:

$$E_t = \left(\kappa_c E_{c,t}^{\frac{\varepsilon-1}{\varepsilon}} + \kappa_s E_{s,t}^{\frac{\varepsilon-1}{\varepsilon}} + \kappa_g E_{g,t}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}.$$

  - $E_{c,t}$, $E_{s,t}$, and $E_{g,t}$ $\sim$ coal, natural gas, and green energy, resp.

Energy production

- Production of energy $i \in \{c, s, g\}$ is given by:

$$E_{i,t} = \min\left(Q_{it}, R_{it}\right),$$

  - $Q_{it} \sim$ energy input (e.g., power plant); $R_{it} \sim$ resource (e.g., coal)
  - Green resource is free but extraction of natural gas and coal is costly

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- Energy input i ("power plant") is produced according to:

$$Q_{it} = \exp\left(\int_0^1 \ln q_{ijt}\, dj\right)$$

- q_{ijt}: Intermediate inputs (e.g., steam turbine, boiler, etc.)
  - Produced by monopolist j in energy sector i via $q_{ijt} = A_{ijt} l_{ijt}^q$
  - Monopolist's technology γ times more productive than fringe

$\longrightarrow$ *Avg. productivity in power plant type i*: $\ln A_{it} = \int_0^1 \ln A_{ijt}\, dj$

$\longrightarrow$ **Endogenous**

Resource production

- Extracting 1 unit of coal or gas requires 1 unit of extraction input
  - Extraction input is produced symmetrically to power plant input
  - E.g., gas well is aggregate of intermediates (drill, proppants, etc.)

- Denote B_{it} the extraction productivity (exogenous).
  - Shale gas boom = increase in B_{st}.

- Coal and gas in infinite supply: resource price = extraction cost
- Resource use leads to pollution with $P_{i,t} = \xi_i R_{i,t}$ and

$$\xi_c > \xi_s > 0 = \xi_g$$

Short-Run Impacts of the Shale Gas Boom

- Consider a one time increase in gas extraction technology B_{st}

$$\frac{\partial \ln \text{Emissions}}{\partial \ln B_{st}} = \underbrace{\frac{\partial \ln \text{Emissions Intensity}}{\partial \ln B_{st}}}_{\substack{\text{Substition out of} \\ \text{coal, green}}} + \underbrace{\frac{\partial \ln \text{Energy}}{\partial \ln B_{st}}}_{\text{Scale Effect}}$$

Proposition

The shale gas boom leads to a decrease in emissions in the short-run provided that natural gas is sufficiently clean compared to coal.

Details

Innovation

- There is a mass 1 of scientists who can decide in which sector to work
  - $s_{ft} \sim$ share working on fossil fuels generation technology
  - $s_{gt} \sim$ share working on green generation technology

- Each scientists has a probability of success given by: $\eta_i s_{it}^{-\psi}$

- A successful innovator obtains a technology γ times more productive
  - Patents last for 1 period only
  - If there is no innovation, monopoly rights are allocated randomly

- Marginal scientist indifferent btwn. innovating in fossil fuels or green

Innovation allocation

- The sector with the largest profits attract most scientists. (up to an adjustment for η_i) Details

- More advanced sector gets a larger market $\Rightarrow$ Larger profits from further innovation
  - Better green technology $A_{g(t-1)}$ leads to more green innovation
  - Better gas technology $A_{s(t-1)}$ leads to more fossil innovation (under some regularity conditions).

- Improvement in gas extraction technology B_{st}:
  - Extraction and power plant are complements $\Rightarrow$ Higher gas extraction technology B_{st} encourages innovation in gas generation A_{st}

Shale gas boom and innovation

Proposition

i) A shale gas boom (an increase in B_{s1}) leads to reduced innovation in green technologies at $t = 1$ (i.e., to a decrease in s_{g1}).

ii) Green innovation declines for all $t \geq 1$ under suitable conditions.

Details

- Effect of the shale boom on innovation builds on itself over time

Endogenous B

Long-run equilibrium (constant extraction technologies).

- Long-run equilibrium depends on future extraction technology

1) If fossil fuel extraction productivities (B_{ct}, B_{st}) remain *constant* after the boom, then:

- Fossil resources become relatively more expensive over time
- Eventually, innovation moves to the clean sector

⇒ **Shale gas boom (i) delays clean energy transition and (ii) increases emissions in the long-run***

Prop.

Long-run equilibrium (growing extraction technologies)

2) If fossil fuel extraction productivities (B_{ct}, B_{st}) *grow* at constant rate after the boom, then:

- Path dependence dominates and innovation allocation is bang-bang

⇒ **Shale gas boom makes fossil-fuel path more likely** Prop.

- Three cases depending on initial green generation technology A_{gt}
  - Low A_{gt}: Shale boom hastens transition to all-fossil economy
  - Interm. A_{gt}: Shale boom pushes economy from green to fossil path
  - High A_{gt}: Shale boom delays transition to green economy

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3. **Quantitative Model**
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Benchmark Setup

- Production inputs now capital-labor aggregates:

$$
\begin{aligned}
Y_{Pt} &= A_{Pt} L_{Pt}^{\varphi} K_{Pt}^{1-\varphi} \\
q_{ijt} &= A_{ijt} \left(l_{ijt}^{q}\right)^{\phi} \left(k_{ijt}^{q}\right)^{1-\phi} \text{ and } r_{ijt} = B_{ijt} \left(l_{ijt}^{r}\right)^{\phi} \left(k_{ijt}^{r}\right)^{1-\phi}
\end{aligned}
$$

- Different elasticities of substitution between (coal, gas), green:

$$
E_t = \left(\left(\kappa_c E_{c,t}^{\frac{\sigma-1}{\sigma}} + \kappa_s E_{s,t}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}\frac{\varepsilon-1}{\varepsilon}} + \kappa_g E_{g,t}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}
$$

- Account for local pollutants (e.g., SO_2) and abatement costs $\overline{\Lambda_i}$:

$$
\underbrace{p_{it}}_{\text{Energy price } i} = \underbrace{p_{it}^{r}}_{\text{Resource price } i} + \underbrace{p_{it}^{q}}_{\text{Input price } i} \left(1 + \overline{\Lambda_i}\right)
$$

Calibration (1)

- Obtain micro-data of U.S. electricity generators' costs and outputs.

Item	Data Source(s)
Plant capital, Labor, O&M, output -> Annualized KL-costs/MWh $p^q_{it}(1+\overline{\Lambda_i})$	Federal Energy Regulatory Commission (FERC) "Form 1" Filings
Local pollution abatement capital, O&M expenditures -> costs/MWh $p^q_{it}\overline{\Lambda_i}$	EIA Form 767, 923
Fuel resource costs/MWh p^r_{it}	FERC Form 423 EIA Forms 423, 923

- For renewables, supplement with Lazard (2008-2010) cost estimates

Calibration (2)

- Parameters from the literature:
  - $\varepsilon = 1.8561$, Papageorgiou et al. (2013)
  - $\sigma = 2$, Bosetti et al. (2007), Ko and Dahl (2001), Sonderholm (1991)
  - $\lambda = 0.5$, Chen et al. (2017), Van der Werf (2008), Bosetti et al. (2007)
  - Labor shares: $\phi = 0.403$ (Barrage, 2019) and $\varphi = 0.67$
- $\gamma = 1.07$, Match 2004-2014 industry profits data (U.S. Census)
  - Petroleum and Coal, Durable Manufacturing, Wholesale
- Base period: 2006-2010
  - We get initial aggregate capital K_0 (BEA).
- Shale boom effect on B_s :
  - Based on relative coal, gas resource price changes: $+100\%$
  - Alternative based on simple gas price change: $+54\%$

Calibration (4)

- Solve for initial technology levels (A_{g0},A_{c0},A_{s0},B_{c0},B_{s0}, $A_{P,0}$, $\widetilde{A_{E,0}}$) and energy aggregator distribution parameters (κ_c, κ_s, κ_g) to jointly match data moments:
  - GDP (BEA)
  - Electricity generation (coal, gas, green) (EIA)
  - Generation costs (coal, gas, green) (FERC, EIA, NREL)
  - Employment share in extraction, electricity, gen. manuf. (BLS)

Short-Run Impact Estimates

Total Effects of Improved Shale Extraction Technology B_{s0}			
	$\%\Delta$Emiss.	$\%\Delta$Energy	$\%\Delta CO_2$
	Intensity	Consumption	Emissions
Baseline Parameters			
+50% Increase in B_{s0}	-9.2%	+5.8%	-4.0%
+100% Increase in B_{s0}	-13.5%	+10.3%	-4.5%

Sensitivity

- Cullen and Mansur (2017) empirically estimate 10% CO2 emissions intensity declines in short-run for a 67% decline in gas prices.
- Data: 2006-10 vs. 2011-15: Emissions intensity decline 11.35%.

Calibration (5): Dynamics

- 1 period = 5 years

- Recall scientists' probability of success: $\eta_i s_{it}^{-\psi}$
- Set $\eta_f = \eta_g$ and growth rate of production input technology A_{Pt} to match balanced long-run growth of 2%/year

$\Rightarrow$ Set $\psi = 0.552$ to match empirical estimates of price elasticity of green innovation w.r.t. natural gas price (0.35)

Calibration (5): Dynamics

- 1 period = 5 years

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- Set $\eta_f = \eta_g$ and growth rate of production input technology A_{Pt} to match balanced long-run growth of 2%/year

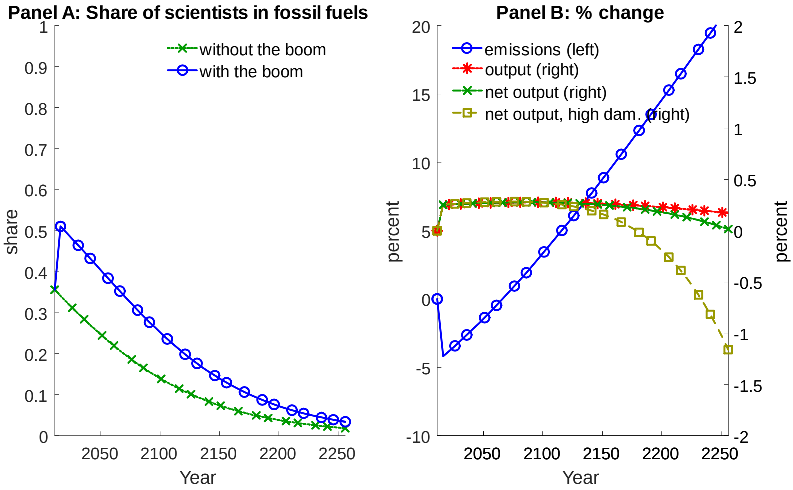
$\Rightarrow$ Set $\psi = 0.552$ to match empirical estimates of price elasticity of green innovation w.r.t. natural gas price (0.35)

- Carbon cycle and damages from Golosov et al. (2014)
  - ROW, U.S. non-electricity emissions from RICE (exogenous here)
  - $\rho = 1.5\%$ per year and elasticity of intertemporal substitution $= 1/2$

- Let K grows exogenously (orthogonal to our analysis).

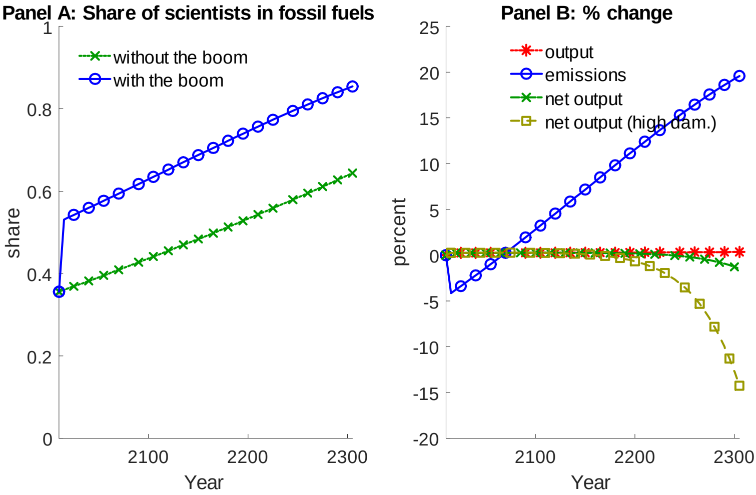
Unmanaged boom (constant extraction technology)

- Effect of one-time 100% increase in gas extraction technology B_{st}:



Unmanaged boom results (growing extraction technology)

- Effect of one-time 100% increase in gas extraction technology B_{st}
- Benchmark $\sim$ "Low A_{gt}"



Data vs. Model: Emissions Intensity

Time	Model $\Delta\xi_E$	Actual $\Delta\xi_E$	Scenario
2006-2010			
vs.	-13.46%	-11.35%	Static
2011-2015	-14.09%		Constant B
	-13.17%		Growing B

Data vs. Model: Innovation Ratio

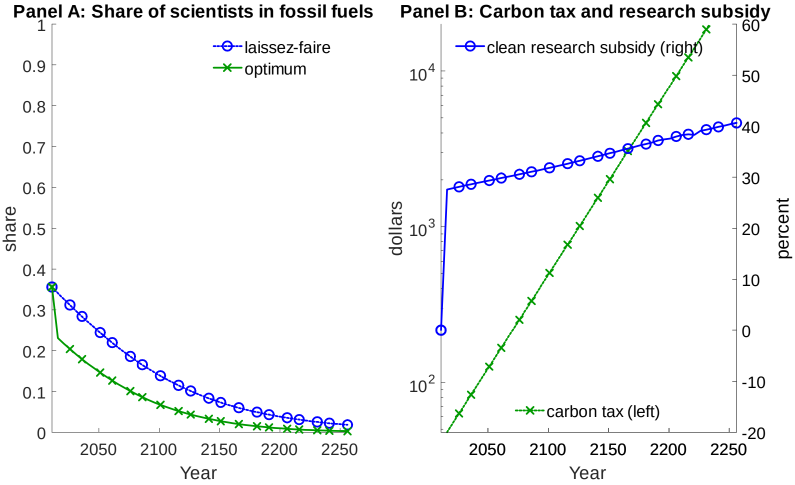
Time	Model $\frac{\text{Patents}_{gr\epsilon n}}{\text{Patents}_{\text{fossil}}}$	Data $\frac{\text{Patents}_{gr\epsilon n}}{\text{Patents}_{\text{fossil}}}$	Scenario
2006-2010	1.31	1.47	Constant B
2011-2015	0.98	0.99	Constant B
2006-2010	1.31	1.47	Growing B
2011-2015	0.95	0.99	Growing B

Optimal policy: Setup

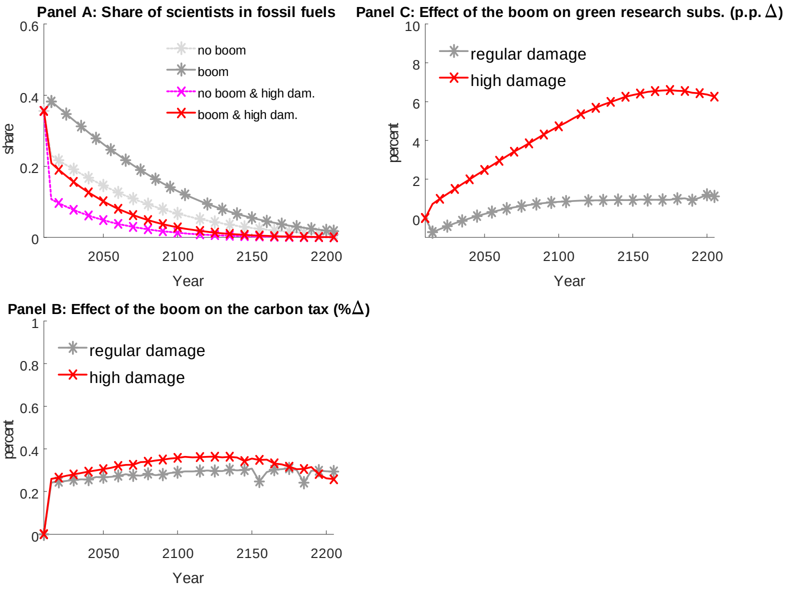
- Consider a social planner who maximizes US welfare but takes emissions from ROW (and outside electricity) as given
  - Free-riding ⇒ policy is not ambitious enough.
  - Optimal tax level higher with emissions spillovers, but unmanaged boom impacts similar. Details

- Two externalities ⇒ two instruments:
  - Carbon tax to correct for environmental externality.
  - Clean research subsidy to take into account that private value of innovation is too short-sighted.

Optimal Policy Levels (No Boom, Const. Extr. Tech.)



Effect of shale gas boom on optimal policy



Summary

- Motivating stylized fact: Green innovation decline after shale boom

⇒ Directed technical change model; find theoretically & quantitatively:

  - Boom decreased CO_2 emissions in short-run, but:
  - But increase CO_2 emissions in long-run through innovation channels

⇒ Call for stronger policy responses to address climate change.

- Qunatitivate results similar in Extended Model with:
  - Distinct coal and natural gas innovation
  - BAU policies

- Open questions: Cross-country differences in baseline shale boom impacts, rising extraction costs from depletion (Schwerhoff and Sturmer, 2019), ... Stephie's comments!

Extended version: Overview

- So far: All fossil innovation advances coal, gas proportionally

$\Rightarrow$ Allow for distinct innovation in gas vs. coal

- So far: zero base period innovation subsidies

$\Rightarrow$ Allow initial subsidies for innovation in coal q_c, gas q_s, and green q_g

- So far: zero base period generation subsidies, taxes

$\Rightarrow$ Allow initial subsidies for generation w/ coal τ_c, gas τ_s, and green τ_g

Separating coal vs gas innovation (1)

- Background (Lanzi et al., 2011):

Table 1: Selected efficiency-improving technologies for fossil-fuel electricity generation

	Technology	Application
Fuel preparation technologies	Coal gasification	Coal
	Coal pulverisation	Coal
	Coal drying	Coal
Furnaces and burners	Improved burners	Coal, gas, oil
	Fluidised beds	Coal
Boilers, turbines and engines	Improved boilers for steam generation	Coal, gas, oil
	Improved steam engines	Coal, gas, oil
	Super-heaters	Coal, gas, oil
	Improved gas turbines	Coal, gas, oil
	Combined cycles (IGCC, NGCC, CHP)	Coal, gas, oil
	Improved compressed ignition engines	Oil
	CHP & co-generation (of electricity and heat)	Coal, gas, oil

- 'Shared component' specification also in EIA NEMS model Details

Separating coal vs gas innovation (2)

- Distinguish R&D in coal vs. gas generation:
  - Fraction $(1-\chi)$ of coal innovation specific to coal (and v.v.)
  - Fraction χ of coal innovation useful for gas generation (and v.v.)
- Scientists can work in three sectors: s_{ct}, s_{st}, s_{gt}
- Quantification:
  - Set $\chi = 0.855$ to match USPTO 2006-10 green-fossil patent ratio.
  - Set $\eta_g = \eta_f(1+\chi^{\frac{1}{\psi}})^{\psi}$ to ensure equal long-run growth potential.

Base period innovation subsidies

- Allow for base period innovation to already have been subsidized.
- Equilibrium allocation now determined by Details:

$$\frac{\Pi_{ct}}{\Pi_{st}} = \frac{1-q_c}{1-q_s} \text{ and } \frac{\frac{\Pi_{ct}}{1-q_c} + \frac{\Pi_{st}}{1-q_s}}{\frac{\Pi_{gt}}{1-q_g}} = 2$$

- Quantification:
  - NSF "Industrial Research and Development" Survey.
  - "Federal Sources Share" for most recent years available (2000-07).
  - Fossil: 3.9% $= q_c = q_s$
  - Renewables: 9.1%, Nuclear: 45.3% $\rightarrow$ Total R&D spending-weighted $q_g = 21.05\%$

Base period generation subsidies

- Allow for base period generation to already have been taxed
- Quantification:
  - Lazard renewables levelized cost estimates with vs. without subsidies
  - Generation-weighted avg. green generation tax $\tau_g = -3.23\%$
  - Small because of large nuclear generation share
  - Consider $\tau_c = \tau_s = 0$
  - Even by 2015 $< 8\%$ of U.S. electricity-based carbon emissions subject to a price (OECD, 2018)
  - But: Renewable portfolio standards hard to capture
  - Robustness: $\tau_g = 2 \times (-3.23\%)$, $\tau_c = \tau_s = 5\%$

Extended model results overview

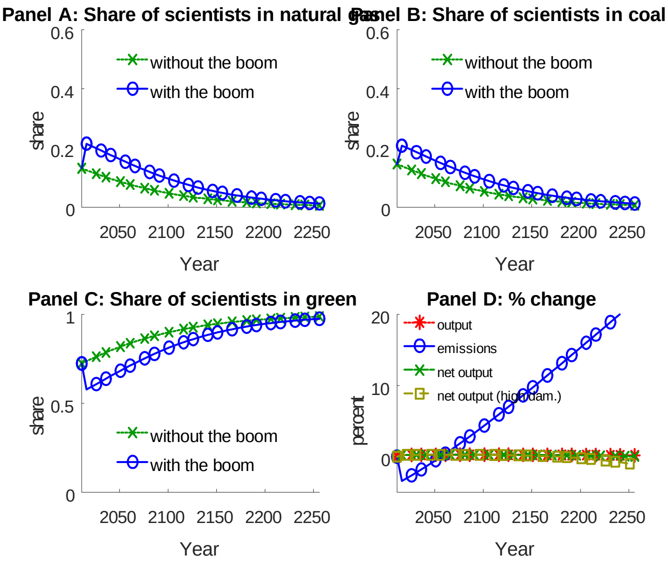
Static Effects			
	%ΔEmiss.	%ΔEnergy	%Δ CO_2
	Intensity	Consumption	Emissions
Benchmark Model	-13.5%	+10.3%	-4.5%
Extended Model	-12.8%	+10.3%	-3.8%
$2 \times \tau_g, \tau_c, \tau_s$ 5%	-13.5%	+10.6%	-4.4%

Extended model results overview

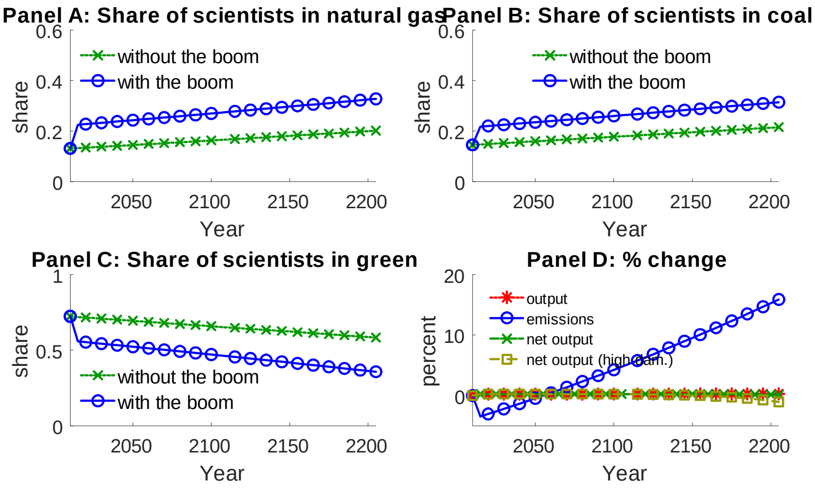
Static Effects			
	%ΔEmiss.	%ΔEnergy	%Δ CO_2
	Intensity	Consumption	Emissions
Benchmark Model	-13.5%	+10.3%	-4.5%
Extended Model	-12.8%	+10.3%	-3.8%
$2 \times \tau_g, \tau_c, \tau_s$ 5%		+10.6%	-4.4%

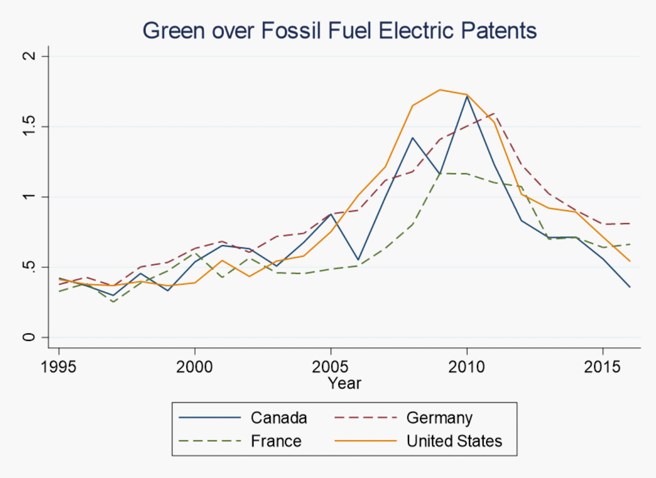
Dynamic Effects				
	2016		2066	
	%Δ $Innov_g$	%Δ CO_2	%Δ $Innov_g$	%Δ CO_2
Benchmark Model	-13.6%	-4.2%	-12.0%	-0.0%
Extended Model	-21.6%	-3.4%	-14.3%	+0.9%
$2 \times \tau_g, \tau_c, \tau_s$ 5%	-23.6%	-4.0%	-16.1%	+0.1%

BAU Results (constant extraction technology)



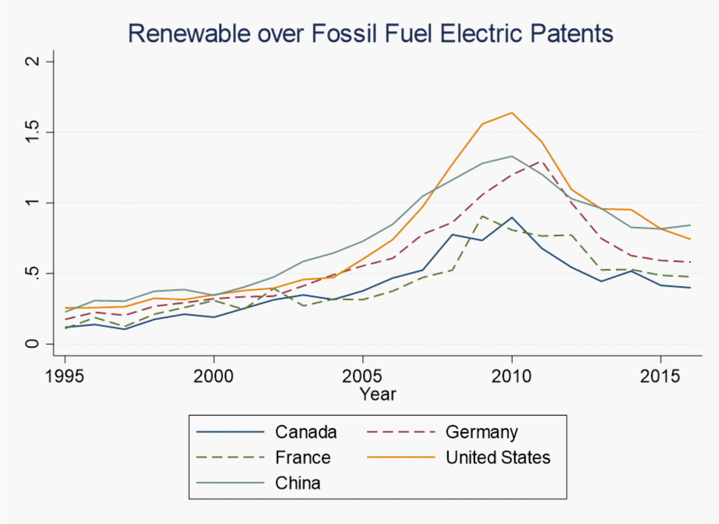
BAU Results (growing extraction technology)




Green over Fossil Fuel Electric Patents
0
.5
1
1.5
2
1995
2000
2005
2010
2015
Year
Canada
Germany
France
United States

Renewables over fossil fuel patents

- Domestic + foreign patents by patent offices



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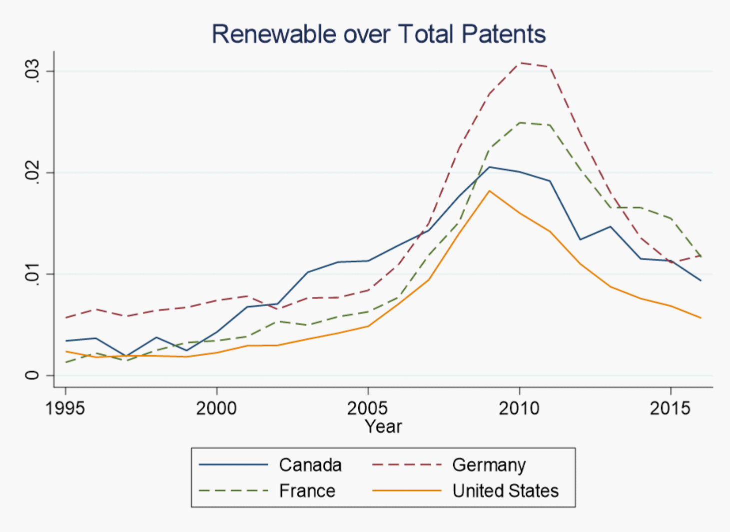
Renewables over total patents



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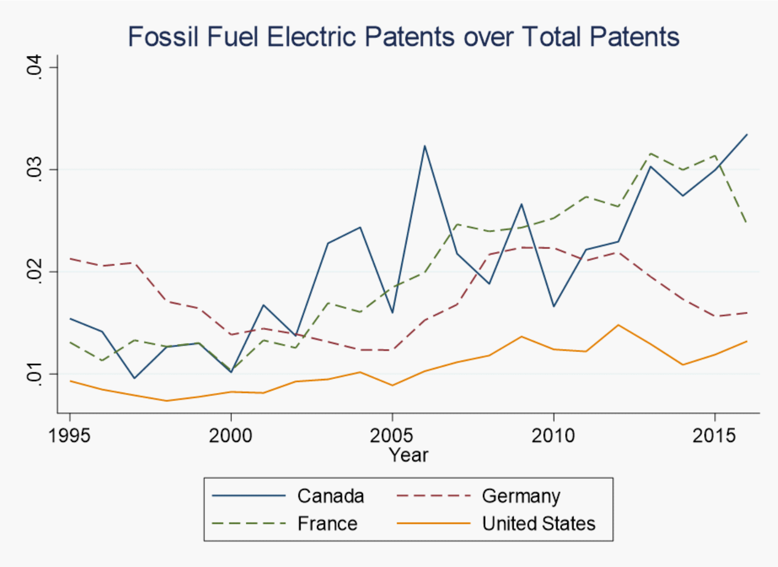
Fossil-fuel / total patents



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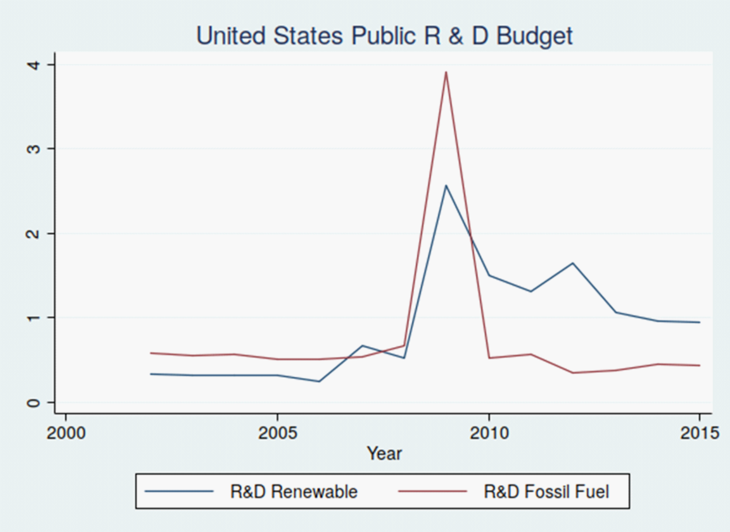
R&D public expenditures



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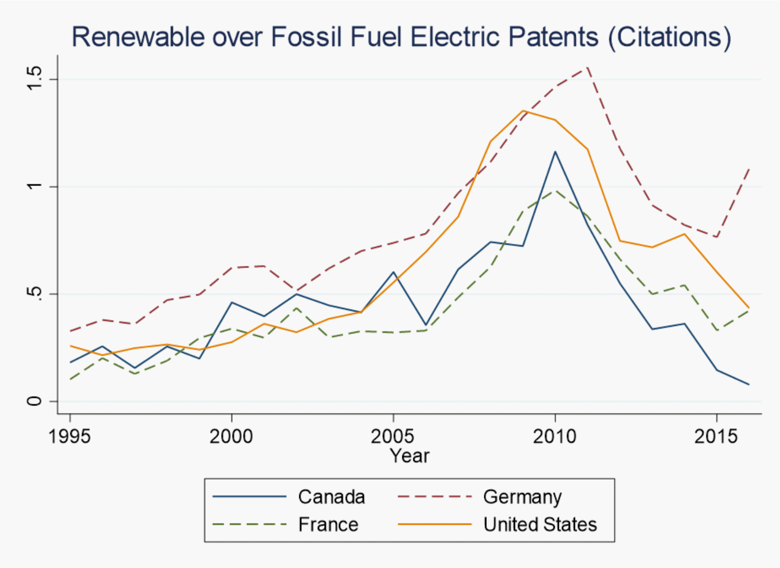
Renewable / Fossil fuel (citations-weighted)



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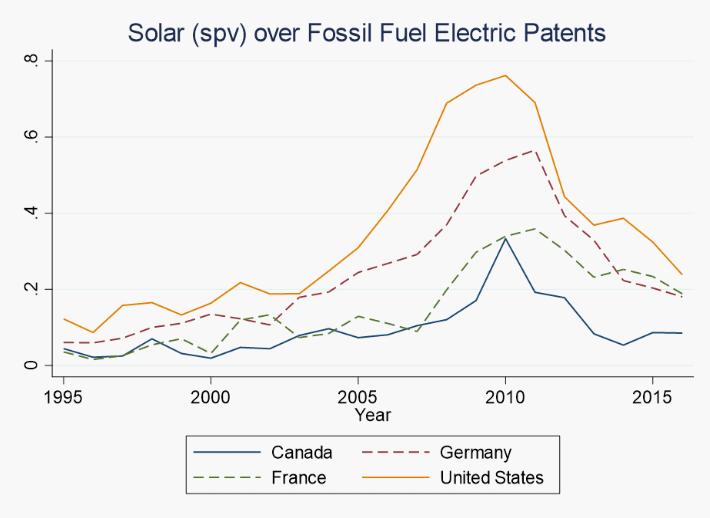
Solar / Fossil-fuel



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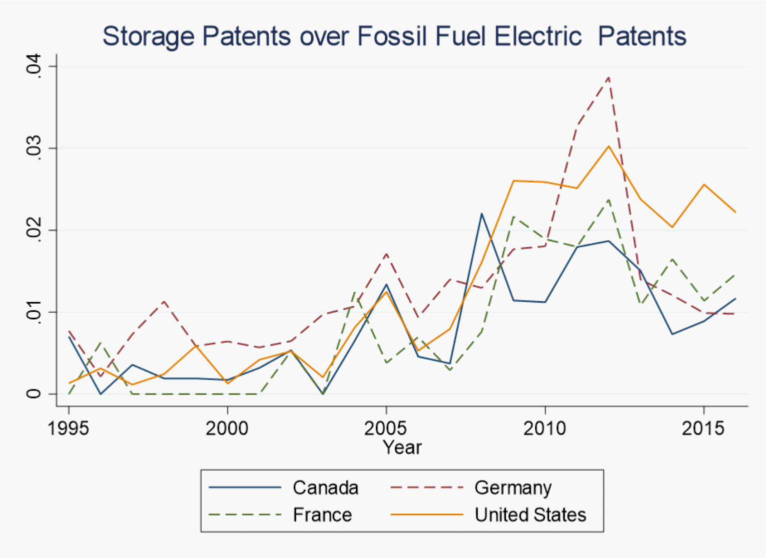
Storage / Fossil-fuel (all)



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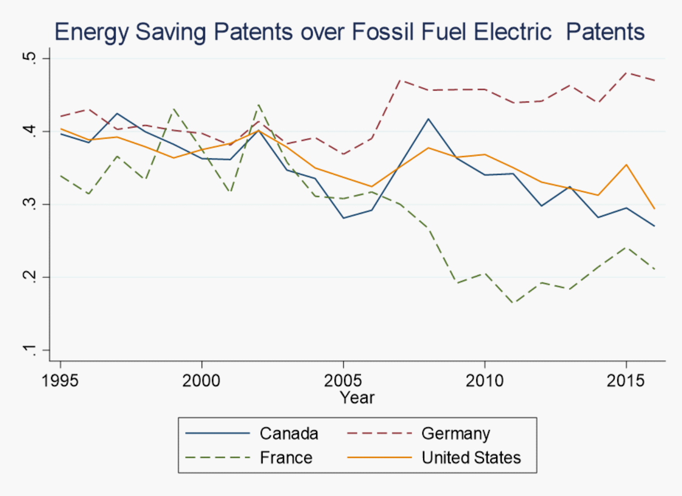
Energy-saving / Fossil-fuel (all)



Natural Gas Prices: granted patents

	Patent Office: All							
	Renewable/Fossil fuel electric				Green/Fossil fuel electric			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Panel A: log (Renewable / Fossil fuel electric)							
ln(Gas Price Index)	0.356**	0.334***	0.338**	0.335***	0.387**	0.379***	0.383***	0.382***
	(0.144)	(0.110)	(0.114)	(0.105)	(0.153)	(0.116)	(0.121)	(0.116)
ln(GDP/cap.)	1.142***	1.138***	1.204*		0.985***	0.980***	1.003	
		(0.225)	(0.234)	(0.575)		(0.299)	(0.316)	(0.621)
ln(Public R&D Fossil)			-0.004	-0.004			0.007	0.006
			(0.056)	(0.059)			(0.049)	(0.049)
ln(Public R&D Green)			0.045	0.048			0.044	0.045
			(0.030)	(0.045)			(0.026)	(0.039)
ln(Energy consumption)				-0.059				-0.020
				(0.391)				(0.441)
Obs.	310	305	305	305	314	307	307	307
Countries	14	14	14	14	14	14	14	14
Adj. R^2	0.819	0.832	0.831	0.830	0.742	0.795	0.795	0.794

Note: Independent variable and controls lagged 2 periods, star levels: * 0.10, ** 0.05, *** 0.010. All regressions include country and year fixed effects. Standard errors are clustered at the country-level. Includes: AU, BE, CA, CH, DE, FR, GB, GR, JP, KR, MX, NZ, SK, US.

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Natural Gas Prices: weighted regressions

	Patent Office: All							
	Renewable/Fossil fuel electric				Green/Fossil fuel electric			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Panel A: log (Renewable / Fossil fuel electric)							
ln(Gas Price Index)	0.260**	0.204**	0.207**	0.211**	0.322***	0.281***	0.287***	0.300***
	(0.109)	(0.080)	(0.078)	(0.074)	(0.106)	(0.083)	(0.080)	(0.074)
ln(GDP/cap.)		1.064***	1.045***	0.949**		0.838***	0.805***	0.443
		(0.083)	(0.085)	(0.413)		(0.092)	(0.085)	(0.346)
ln(Public R&D Fossil)			-0.037	-0.036			-0.023	-0.022
			(0.026)	(0.026)			(0.034)	(0.034)
ln(Public R&D Green)			0.031***	0.030***			0.045**	0.041**
			(0.008)	(0.008)			(0.017)	(0.016)
ln(Energy consumption)				0.075				0.282
				(0.284)				(0.249)
Obs.	46	340	340	340	347	340	340	340
Countries	15	15	15	15	15	15	15	15
Adj. R^2	0.938	0.957	0.957	0.957	0.925	0.944	0.945	0.945

Note: Independent variable and controls lagged 2 periods, star levels: * 0.10, ** 0.05, *** 0.010. All regressions include country and year fixed effects. Standard errors are clustered at the country-level. Includes: AU, BE, CA, CH, CZ, DE, FR, GB, GR, JP, KR, MX, NZ, SK, US.

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Natural Gas Prices: Domestic Inventors Only (weighted)

	Patent Office: Same							
	Renewable/Fossil fuel electric				Green/Fossil fuel electric			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Panel A: log (Renewable / Fossil fuel electric)							
ln(Gas Price Index)	0.302	0.310	0.481**	0.433**	0.332	0.341	0.459***	0.422***
	(0.284)	(0.296)	(0.186)	(0.172)	(0.199)	(0.212)	(0.130)	(0.130)
ln(GDP/cap.)		0.962***	0.901***	3.147*		1.133***	1.092***	2.853**
		(0.055)	(0.120)	(1.626)		(0.082)	(0.122)	(0.993)
ln(Public R&D Fossil)			-0.028	0.011			0.026	0.057
			(0.109)	(0.097)			(0.081)	(0.065)
ln(Public R&D Green)			0.135	0.115			0.082	0.067
			(0.160)	(0.140)			(0.096)	(0.076)
ln(Energy consumption)				-1.562				-1.226
				(1.103)				(0.701)
Obs.	269	268	268	268	276	274	274	274
Countries	14	14	14	14	14	14	14	14
Adj. R^2	0.813	0.839	0.842	0.848	0.826	0.878	0.881	0.886

Note: Independent variable and controls lagged 2 periods, star levels: * 0.10, ** 0.05, *** 0.010. All regressions include country and year fixed effects. Standard errors are clustered at the country-level. Includes: AU, BE, CA, CH, DE, FR, GB, GR, JP, KR, MX, NZ, SK, US.

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"Diff-in-Diff" Comparison

- Shale boom: 2009 + 2 year lag (US and Canada) (Holladay and Jacob LaRiviere, 2017)
  - Construct panel of shale boom *bans* across countries. Period 2001-2016.

Patent Office: All

	Renewable/Fossil electric				Green/Fossil electric			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Shale Gas Boom	-0.231*	-0.368**	-0.253**	-0.353**	-0.211*	-0.337**	-0.222*	-0.296**
	(0.115)	(0.149)	(0.114)	(0.138)	(0.105)	(0.138)	(0.122)	(0.140)
ln(GDP/cap.)	-0.136	-0.409	-0.134	-0.411	-0.067	-0.404	-0.066	-0.409
	(0.546)	(0.437)	(0.546)	(0.439)	(0.544)	(0.433)	(0.545)	(0.436)
Ban		0.192		0.194		0.156		0.161
		(0.188)		(0.190)		(0.237)		(0.240)
Public R&D Fossil			-0.055	0.005			-0.058	0.014
			(0.073)	(0.069)			(0.087)	(0.082)
Public R&D Green			0.054	-0.021			0.043	-0.058
			(0.119)	(0.113)			(0.128)	(0.128)
Fixed Effects (C,T)	Y	Y	Y	Y	Y	Y	Y	Y
Obs.	608	316	608	316	608	316	608	316
Countries	38	20	38	20	38	20	38	20
Adj. R^2	0.609	0.725	0.609	0.725	0.608	0.726	0.608	0.726

*** p<0.01, ** p<0.05, * p<0.1
Note: The shale gas boom is dated from 2009. Independent variables lagged 2 periods. Standard errors clustered at the country-level. Even columns include AU, CA, CH, CL, CN, CZ, DE, DK, ES, FR, GB, HU, IE, IL, JP, PL, PT, NL, NZ, US; odd columns also include TW, AT, BE, IS, EE, FI, GR, IT, KR, LV, LT, LU, MX, NO, SK, SI, SE, TR.

"Diff-in-Diff" Comparison: Domestic Patents

Patent Office: Domestic

	Renewable/Fossil electric				Green/Fossil electric			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Shale Gas Boom	-0.537**	-0.606	-0.392	-0.466	-0.555**	-0.639	-0.477*	-0.528
	(0.217)	(0.388)	(0.271)	(0.366)	(0.217)	(0.397)	(0.269)	(0.371)
ln(GDP/cap.)	-0.958	-1.416	-0.977	-1.434	-1.230	-1.474	-0.981	-1.488
	(1.270)	(1.466)	(1.272)	(1.484)	(1.407)	(1.588)	(1.351)	(1.607)
Ban		-0.061		-0.054		-0.248		-0.243
		(0.716)		(0.715)		(0.870)		(0.870)
Public R&D Fossil			-0.097	-0.189			-0.079	-0.190
			(0.239)	(0.287)			(0.246)	(0.299)
Public R&D Green			-0.134	-0.080			-0.104	-0.043
			(0.310)	(0.308)			(0.320)	(0.308)
Fixed Effects (C,T)	Y	Y	Y	Y	Y	Y	Y	Y
Obs.	583	300	583	300	548	300	583	300
Countries	38	20	38	20	38	20	38	20
Adj. R^2	0.454	0.485	0.452	0.482	0.453	0.478	0.450	0.474

*** p<0.01, ** p<0.05, * p<0.1

Note: The shale gas boom is dated from 2009. Independent variables lagged 2 periods. Standard errors clustered at the country-level. Even columns include AU, CA, CH, CL, CN, CZ, DE, DK, ES, FR, GB, HU, IE, IL, JP, PL, PT, NL, NZ, US; odd columns also include TW, AT, BE, IS, EE, FI, GR, IT, KR, LV, LT, LU, MX, NO, SK, SI, SE, TR.

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Short-Run Impacts of the Shale Gas Boom

$$\frac{\partial \ln P}{\partial \ln B_s} = \frac{C_s}{B_s} \left(\underbrace{\varepsilon \left(\frac{\xi_s E_s}{\xi_c E_c + \xi_s E_s} - \frac{p_s E_s}{p_E E} \right)}_{\text{substitution effect}} + \underbrace{\frac{p_s E_s}{p_E E} \left(\lambda + (1-\lambda) \frac{L_E}{L} \right)}_{\text{scale effect}} \right).$$

Proposition 1: *A shale boom (one-time increase in B_s) decreases emissions in the short-run provided that natural gas is sufficiently clean compared to coal, that is, provided that the following condition is satisfied:*

$$\frac{\xi_s}{\xi_c} < \frac{\kappa_c^\varepsilon C_c^\varepsilon \left[\varepsilon - \left(\lambda + (1-\lambda) \frac{\nu^\lambda \widetilde{A}_{Et}^{\lambda-1} C_E^{\lambda-1}}{\nu^\lambda \widetilde{A}_{Et}^{\lambda-1} C_E^{\lambda-1} + (1-\nu)^{\lambda-1} A_P^{\lambda-1}} \right) \right]}{\kappa_s^\varepsilon C_s^\varepsilon \left(\lambda + \frac{(1-\lambda)\nu^\lambda \widetilde{A}_{Et}^{\lambda-1} C_E^{\lambda-1}}{\nu^\lambda \widetilde{A}_{Et}^{\lambda-1} C_E^{\lambda-1} + (1-\nu)^{\lambda-1} A_P^{\lambda-1}} \right) + \varepsilon C_s \left(\kappa_c^\varepsilon C_c^{\varepsilon-1} + \kappa_g^\varepsilon C_g^{\varepsilon-1} \right)}$$

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Shale gas boom and innovation

Proposition

i) A shale gas boom (an increase in B_{s1}) leads to reduced innovation in green technologies at $t = 1$ (i.e., to a decrease in s_{g1}).

ii) Green innovation declines for all $t \geq 1$ if
$\min\left(B_{ct}/A_{c(t-1)},\, B_{st}/A_{s(t-1)}\right) > \gamma^{\eta_f}/(\varepsilon - 1)$ *for all $t > 1$.*

- If $B_{ct}/A_{c(t-1)}$ and $B_{st}/A_{s(t-1)}$ are too low, improving generation technology $A_{s(t-1)}$ or $A_{c(t-1)}$ has little effect on overall coal, gas technology C_{ct} or C_{st}, and thus on attractiveness of fossil innovation.
- Imagine power plant burning moon rocks as fuel
  - Extremely costly extraction (low $B_{moonrock}$)
  - Improving moon rock *boiler* ($A_{moonrock}$) does little to help reduce overall cost of moon rock power generation!

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Long-run equilibrium

Proposition

Assume that B_{ct} *and* B_{st} *are constant over time and that* $\ln(\gamma)\eta < \psi/((\varepsilon-1)(1-\psi))$.
i) Then there exists a time t_{switch} *such that for all* $t > t_{switch}$, $s_{gt} > 1/2$ *and eventually all innovations occurs in green technologies. If* $\varepsilon \geq 2$, *a shale gas boom at* $t = 1$ *delays the time* t_{switch} *and reduces green innovation until then. ii) In addition for* $\varepsilon \geq 2$ *and for* $\ln\gamma$ *small, emissions are increased in the long-run.*

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Long-run equilibrium

Proposition

Assume that (i) B_{ct} *and* B_{st} *grow exogenously at factor* γ^{η}*,*
(ii) $\ln(\gamma)\eta < \psi / ((\varepsilon - 1)(1 - \psi))$*, and (iii)*
$\min(B_{c1}/A_{c0}, B_{s1}/A_{s0}) > \gamma^{\eta}/(\varepsilon - 1)$*. Then a shale gas boom at* $t = 1$ *decreases green innovations for all* $t \geq 1$*. For small enough initial green productivity* A_{g0}*, emissions will grow forever regardless the boom, and for large enough initial* A_{g0}*, emissions converge to zero regardless.*
For an intermediate range of A_{g0}**, emissions grow forever following a shale boom but converge to zero absent the boom**.

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Equilibrium innovation in extended model (1)

- Equilibrium innovation allocation s_{ct}, s_{st}, s_{gt} now satisfies:

1. After-subsidy returns equated between coal, gas:

$$\frac{\Pi_{ct}}{\Pi_{st}} = \frac{1-q_c}{1-q_s}$$

$$\Leftrightarrow \left(\frac{s_{ct}}{s_{st}}\right)^{\psi}$$

$$= \frac{(1-q_s)\left(\frac{\kappa_c^{\sigma}}{(1+\tau_{ct})^{\sigma}} \frac{(1+\Lambda_{ct}(\mu_{ct}))C_{ct}^{\sigma}}{A_{ct}} + \chi \frac{\kappa_s^{\sigma}}{(1+\tau_{st})^{\sigma}} \frac{(1+\Lambda_{st}(\mu_{st}))C_{st}^{\sigma}}{A_{st}}\right)}{(1-q_c)\left(\chi \frac{\kappa_c^{\sigma}}{(1+\tau_{ct})^{\sigma}} \frac{(1+\Lambda_{ct}(\mu_{ct}))C_{ct}^{\sigma}}{A_{ct}} + \frac{\kappa_s^{\sigma}}{(1+\tau_{st})^{\sigma}} \frac{(1+\Lambda_{st}(\mu_{st}))C_{st}^{\sigma}}{A_{st}}\right)}$$

Equilibrium innovation in extended model (2)

- Equilibrium innovation allocation s_{ct}, s_{st}, s_{gt} now satisfies:

1. After-subsidy returns equated between coal, gas:

$$\frac{\Pi_{ct}}{\Pi_{st}} = \frac{1-q_c}{1-q_s}$$

2. After-subsidy returns equated between fossil, green:

$$\frac{(\Pi_{ct}/(1-q_c)) + (\Pi_{st}/(1-q_s))}{(\Pi_{gt}/(1-q_g))} = 2$$

$$\Leftrightarrow \frac{\eta_f C_{ft}^{\varepsilon-\sigma}\left(\frac{s_{ct}^{-\psi}}{1-q_c} + \frac{\chi s_{st}^{-\psi}}{1-q_s}\right)\frac{\kappa_c^{\sigma}}{(1+\tau_{ct})^{\sigma}}\frac{(1+\Lambda_{ct}(\mu_{ct}))C_{ct}^{\sigma}}{A_{ct}} + }{\eta_g \frac{s_{gt}^{-\psi}}{1-q_g}\frac{\kappa_g^{\varepsilon}}{(1+\tau_{gt})^{\varepsilon}} C_{gt}^{\varepsilon-1}} \cdots$$

$$\frac{\left(\frac{\chi s_{ct}^{-\psi}}{1-q_c} + \frac{s_{st}^{-\psi}}{1-q_s}\right)\frac{\kappa_s^{\sigma}}{(1+\tau_{st})^{\sigma}}\frac{(1+\Lambda_{st}(\mu_{st}))C_{st}^{\sigma}}{A_{st}}}{\eta_g \frac{s_{gt}^{-\psi}}{1-q_g}\frac{\kappa_g^{\varepsilon}}{(1+\tau_{gt})^{\varepsilon}} C_{gt}^{\varepsilon-1}} = 2$$

3. $s_{ct} + s_{st} + s_{gt} = 1.$ Back

Endogenous innovation in extraction technologies

- Allow for endogenous innovation in extraction technologies.
  - s_{gt} scientists improve green technology A_{gt},
  - $s_{A_f t}$ scientists improve both fossil fuel power plant technologies A_{ct} and A_{st}
  - $s_{B_s t}$ scientists improve natual gas extraction technology and $s_{B_c t}$ improve coal gas extraction technology.
- Assume equal potential growth on the green path and on the fossil fuel path: $\eta_{B_s} = \eta_{B_c} = \eta_{A_f} = 2^{1-\psi}\eta_g$.

1. There is path dependence in green innovation vs fossil fuel innovations.
2. If on a fossil fuel path and if $\varepsilon \geq 2$, there is path dependence between coal and natural gas extraction.
3. On impact, a shale gas boom reduces green innovation relative to fossil fuel power plant innovation.
   - If $\varepsilon C_s \geq B_s$, it also reduces green innovation absolutely.

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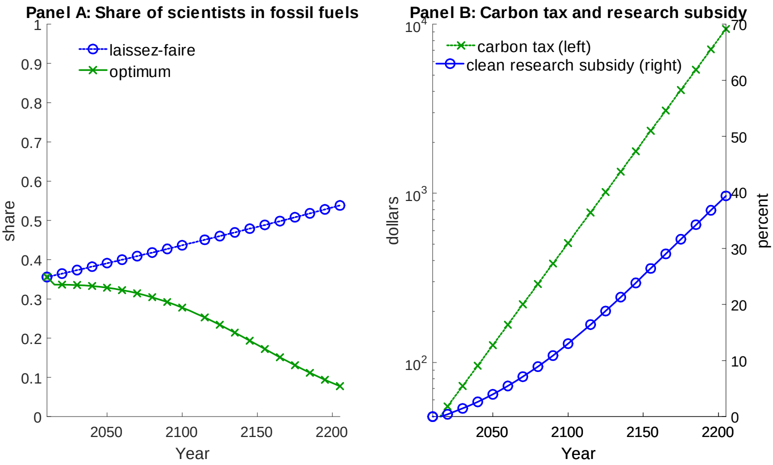
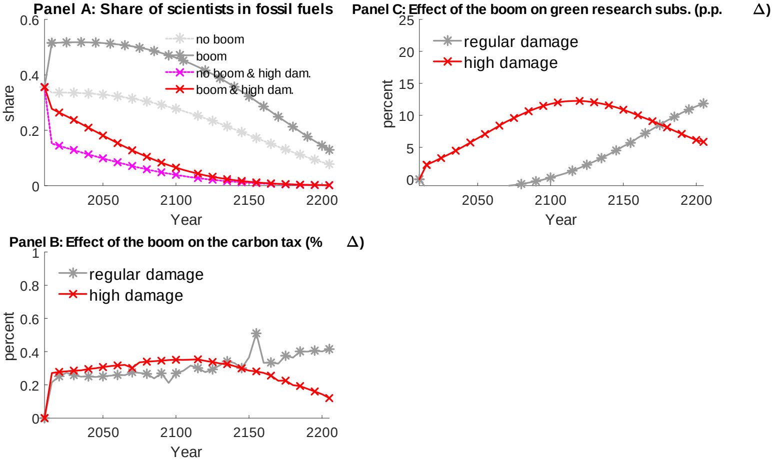
Optimal Policy Levels (No Boom, growing extraction productivity)



Shale Boom Impacts on Optimal Policy (growing extraction productivity)



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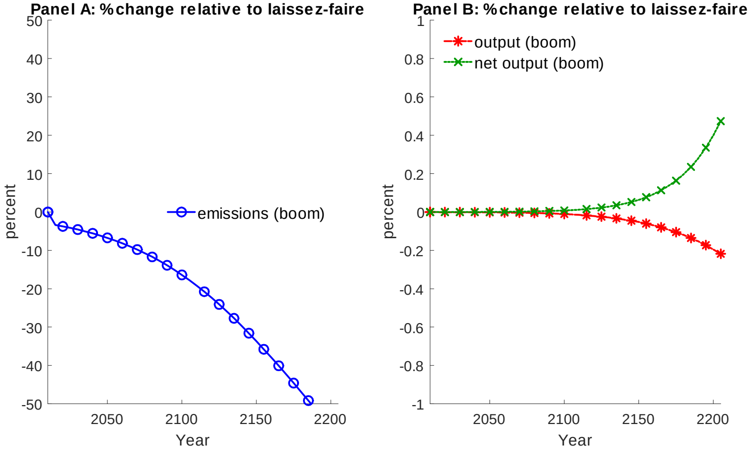
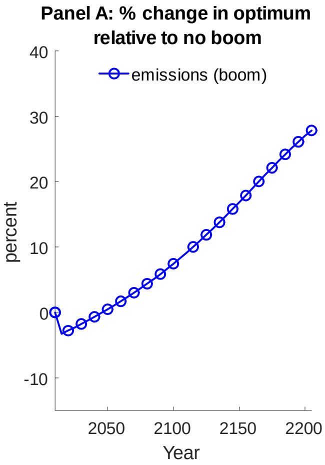
Comparing optimal policy outcomes vs laissez-faire

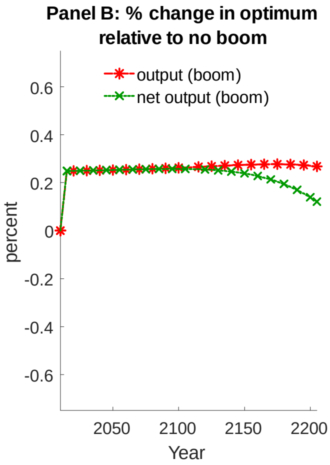
- Growing extraction tech., boom and low damages.



Effect of shale gas boom under optimal policy

- Case with growing extracting technologies and low damages





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Natural Gas Prices: Pre-Boom Sample

Pre-Boom Sample: 1978-2005

	Patent Office: All			
	Renewable/Fossil electric		Green/Fossil electric	
	(1)	(2)	(3)	(4)
ln(Gas Price Index)	0.344**	0.342**	0.255**	0.250***
	(0.135)	(0.144)	(0.091)	(0.083)
ln(GDP/cap.)	1.026***	1.054***	1.317***	1.385***
	(0.146)	(0.192)	(0.296)	(0.321)
Public R&D Fossil		-0.046		-0.062
		(0.119)		(0.094)
Public R&D Green		0.038		0.088***
		(0.045)		(0.028)
Fixed Effects (C,T)	Y	Y	Y	Y
Obs.	211	211	212	212
Countries	15	15	15	15
Adj. R^2	0.750	0.748	0.670	0.672

Note: Independent variables lagged 2 periods. Standard errors clustered at the country-level. Includes AU, BE, CA, CH, CZ, DE, FR, GB, GR, JP, KR, MX, NZ, SK, US.

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Robustness: Tax Controls

	Patent Office: All			
	Renewable/Fossil electric		Green/Fossil electric	
	(1)	(2)	(3)	(4)
ln(Gas Price Index)	0.342**	0.566**	0.250***	0.581*
	(0.144)	(0.201)	(0.083)	(0.312)
ln(GDP/cap.)	1.054***	3.345	1.385***	3.276
	(0.192)	(3.242)	(0.321)	(3.342)
Public R&D Fossil	-0.046	0.150	-0.062	1.535
	(0.119)	(1.229)	(0.094)	(1.314)
Public R&D Green	0.038	0.135	0.088***	0.064
	(0.045)	(0.161)	(0.028)	(0.118)
Coal Tax ($/unit)		-0.001		0.003
		(0.006)		(0.004)
Gas Tax ($/unit)		0.003		0.006
		(0.012)		(0.014)
Fixed Effects (C,T)	Y	Y	Y	Y
Obs.	211	129	212	128
Countries	15	9	15	9
Adj. R^2	0.748	0.679	0.672	0.739

Note: Independent variables lagged 2 periods. Standard errors clustered at the country-level.
Cols. (1) and (3) include AU, BE, CA, CH, CZ, DE, FR, GB, GR, JP, KR, MX, NZ, SK, US.
Cols. (2) and (4) include BE, CH, CZ, DE, FR, GB, JP, MX, SK.

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Emissions Spillovers

- Benchmark: Only U.S. electricity emissions endogenous
  - U.S. non-electric, global emissions exogenous (RICE, Nordhaus, 2011)

- First-pass proxy for technology spillovers: emissions response elasticities

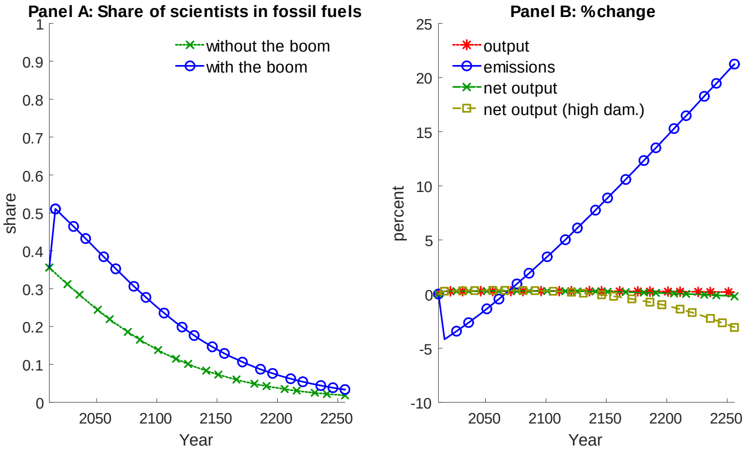
$$\text{Emissions}_t = E_t^{US,Elec} + \overline{E_t^{ROW,Elec}} \cdot (1 + \%\Delta E_t^{US,Elec} \cdot \varepsilon^{Elec})$$

$$+ \left[\overline{E_t^{US,N.Elec}} + \overline{E_t^{ROW,N.Elec}}\right] \cdot (1 + \%\Delta E_t^{US,Elec} \cdot \varepsilon^{N.Elec})$$

- Consider $\varepsilon^{Elec} = 1$ and $\varepsilon^{N.Elec} = 0.1$

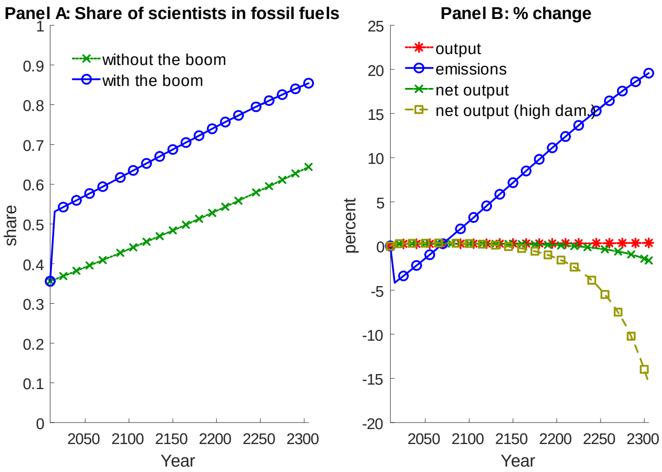
Emissions Spillovers

- Unmanaged boom, constant extraction tech.:



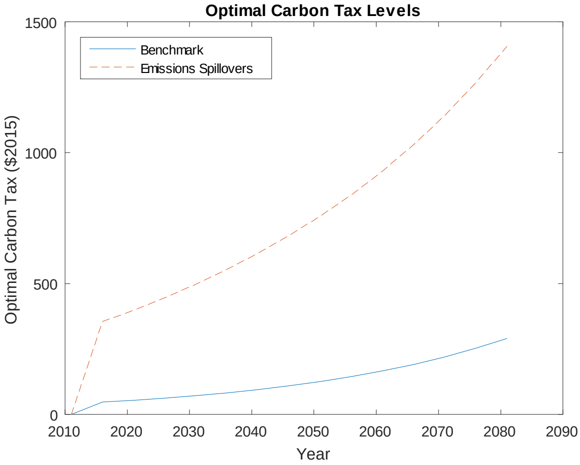
Emissions Spillovers

- Unmanaged boom, growing extraction tech.:



Emissions Spillovers

- Optimal carbon tax (constant extraction tech.)



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Empirical Motivation: Patent Data

- World Patent Statistical Database (PATSTAT): All patents 1970-2015
  - "Fossil fuel" electricity patents: Lanzi, Verdolini and Hascic (2011)
  - "Green" electricity patents: Y02E/10 (renewables); Y02E/50 (biofuels), Y02E/30 (nuclear).
- Allocate patents to the country where they are applied for.
  - Possibly restrict to patents by local inventors as well.

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Short-Run Impact Estimates: Sensitivity

Total Effects of Improved Shale Extraction Technology B_{s0}			
	$\%\Delta$Emiss. Intensity	$\%\Delta$Energy Consumption	$\%\Delta CO_2$ Emissions
$+100\%$ Increase in B_{s0}			
Baseline Parameters	-13.5%	+10.3%	-4.5%
Higher $\varepsilon = 3$	-7.2%	+10.7%	+2.8%
Lower $\varepsilon = 1.5$	-15.6%	+10.2%	-7.0%
Higher $\sigma = 2.2$	-15.9%	+10.6%	-7.0%
Lower $\sigma = 1.8$	-11.0%	+10.0%	-2.1%
Lower $\lambda = 0.3$	-13.5%	+6.2%	-8.1%
Lower p_{g0} (NREL)	-15.9%	+11.2%	-6.5%

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Innovation allocation: details

- Denote *effective productivity of energy type i* as $C_{it} \equiv \left(A_{it}^{-1} + B_{it}^{-1}\right)^{-1}$
  - Let $p_{it} = \gamma w_t / C_{it}$ be the price input of type i.
- An innovator in the green sector obtains expected profits:

$$\Pi_{gt} = \eta_{gt} s_{gt}^{-\psi} \left(1 - \frac{1}{\gamma}\right) p_{gt} E_{gt}$$

- An innovator in the fossil fuel sector obtains expected profits:

$$\Pi_{ft} = \eta_{ft} s_{ft}^{-\psi} \left(1 - \frac{1}{\gamma}\right) \left(\frac{C_{ct}}{A_{ct}} p_{ct} E_{ct} + \frac{C_{st}}{A_{st}} p_{st} E_{st}\right)$$

- In equilibrium, innovators must be indifferent so that $\Pi_{gt} = \Pi_{ft} \Rightarrow$

$$\left(\frac{s_{gt}}{s_{ft}}\right)^{\psi} \approx \frac{\kappa_g^{\varepsilon} A_{gt-1}^{\varepsilon-1}}{\frac{1}{A_{ct-1}} \kappa_c^{\varepsilon} \left(\frac{1}{A_{ct-1}} + \frac{1}{B_{ct}}\right)^{-\varepsilon} + \frac{1}{A_{st-1}} \kappa_d^{\varepsilon} \left(\frac{1}{A_{st-1}} + \frac{1}{B_{st}}\right)^{-\varepsilon}}$$

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