KAIST

The Shale Boom and Green Innovation: Impact of Low Energy Prices on Corporate Patents

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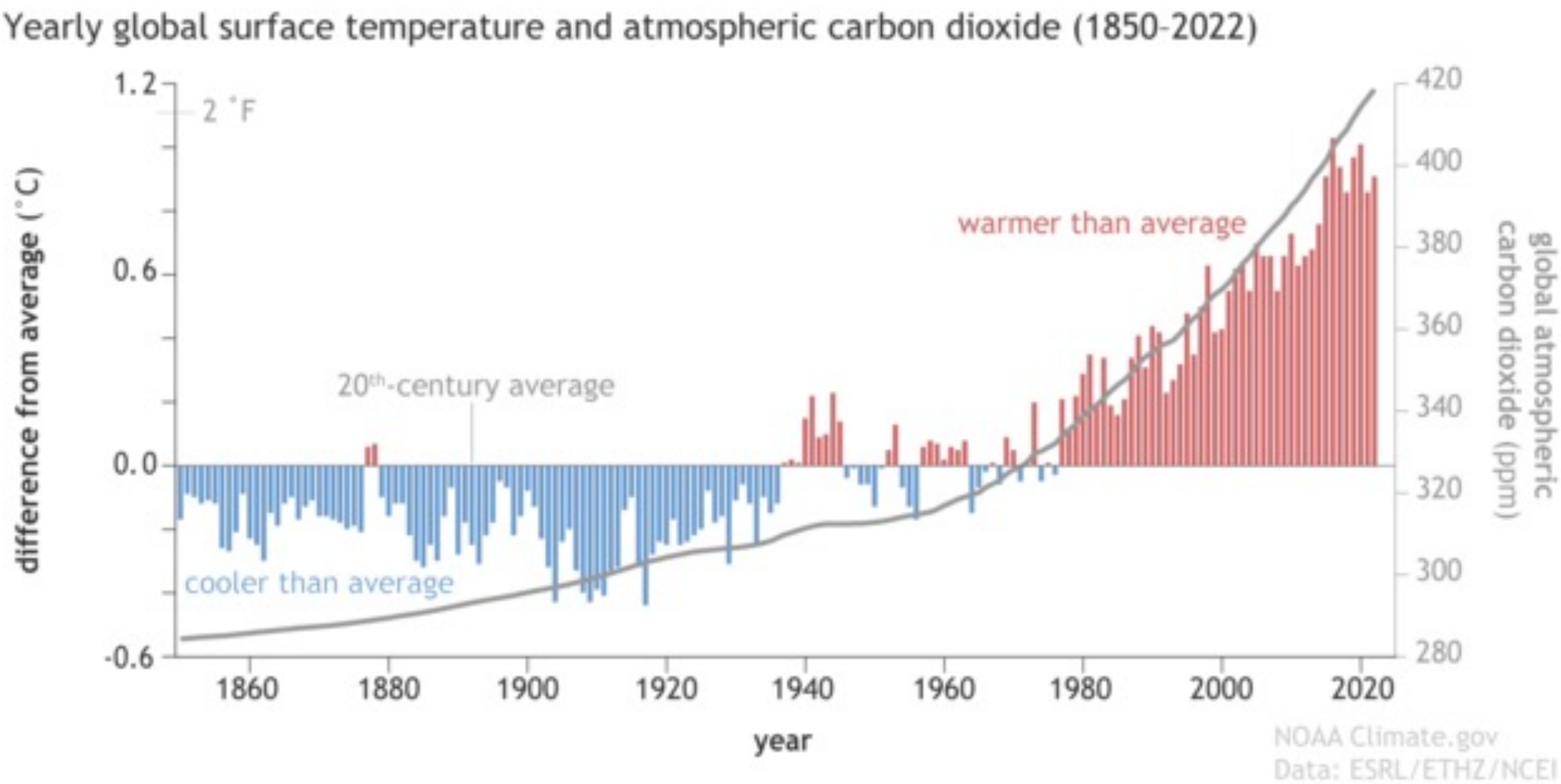
Motivation



- Trends
  - 424 ppm in 2023
  - CO_2 concentration increases at 2-3 ppm annually

Motivation

- Scientists peg 450 ppm as a red line

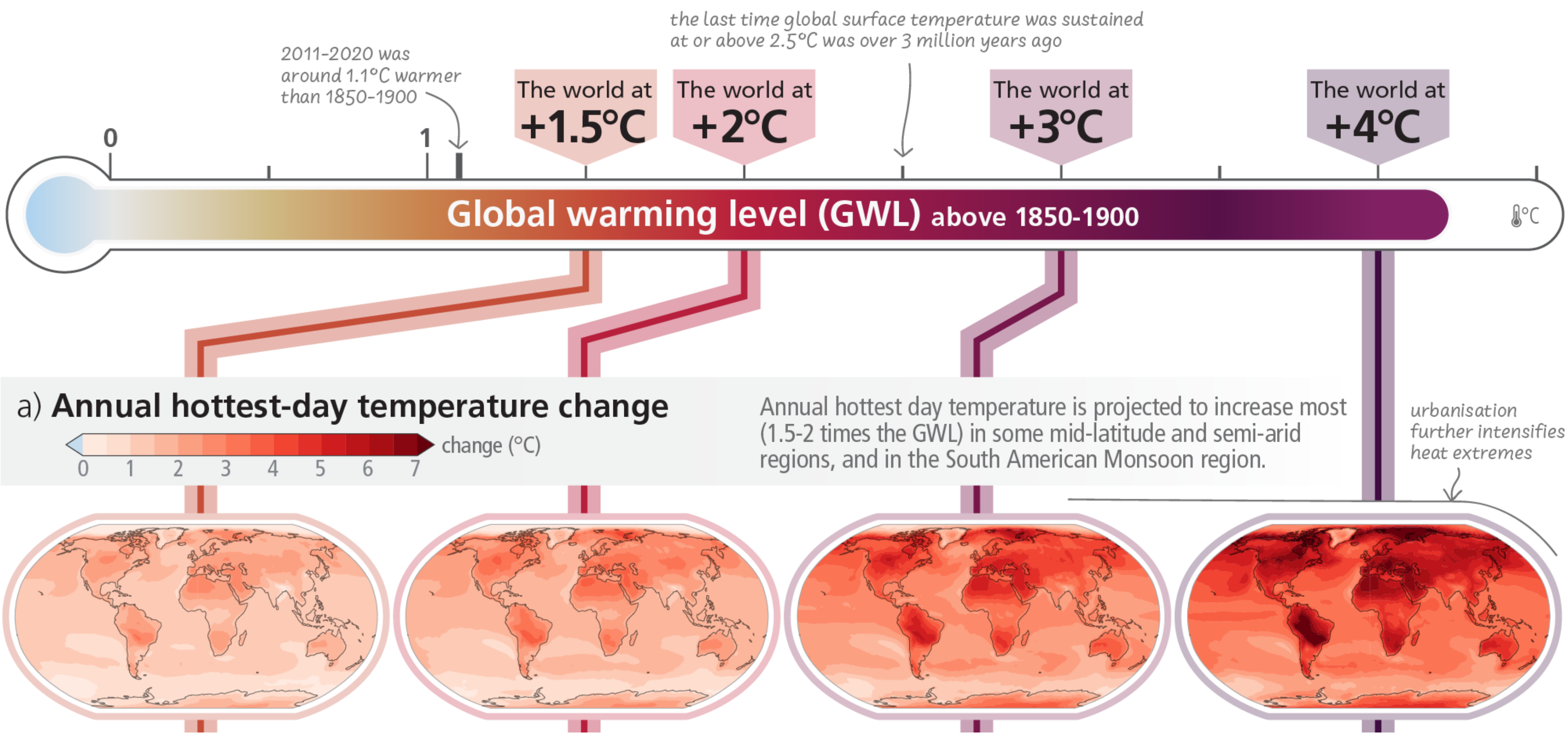
TABLE 1—LIKELIHOOD (IN PERCENTAGE) OF EXCEEDING A TEMPERATURE INCREASE AT EQUILIBRIUM

Stabilization level (in ppm CO_2e)	2°C	3°C	4°C	5°C	6°C	7°C
450	78	18	3	1	0	0
500	96	44	11	3	1	0
550	99	69	24	7	2	1
650	100	94	58	24	9	4
750	100	99	82	47	22	9

IPCC, 2018

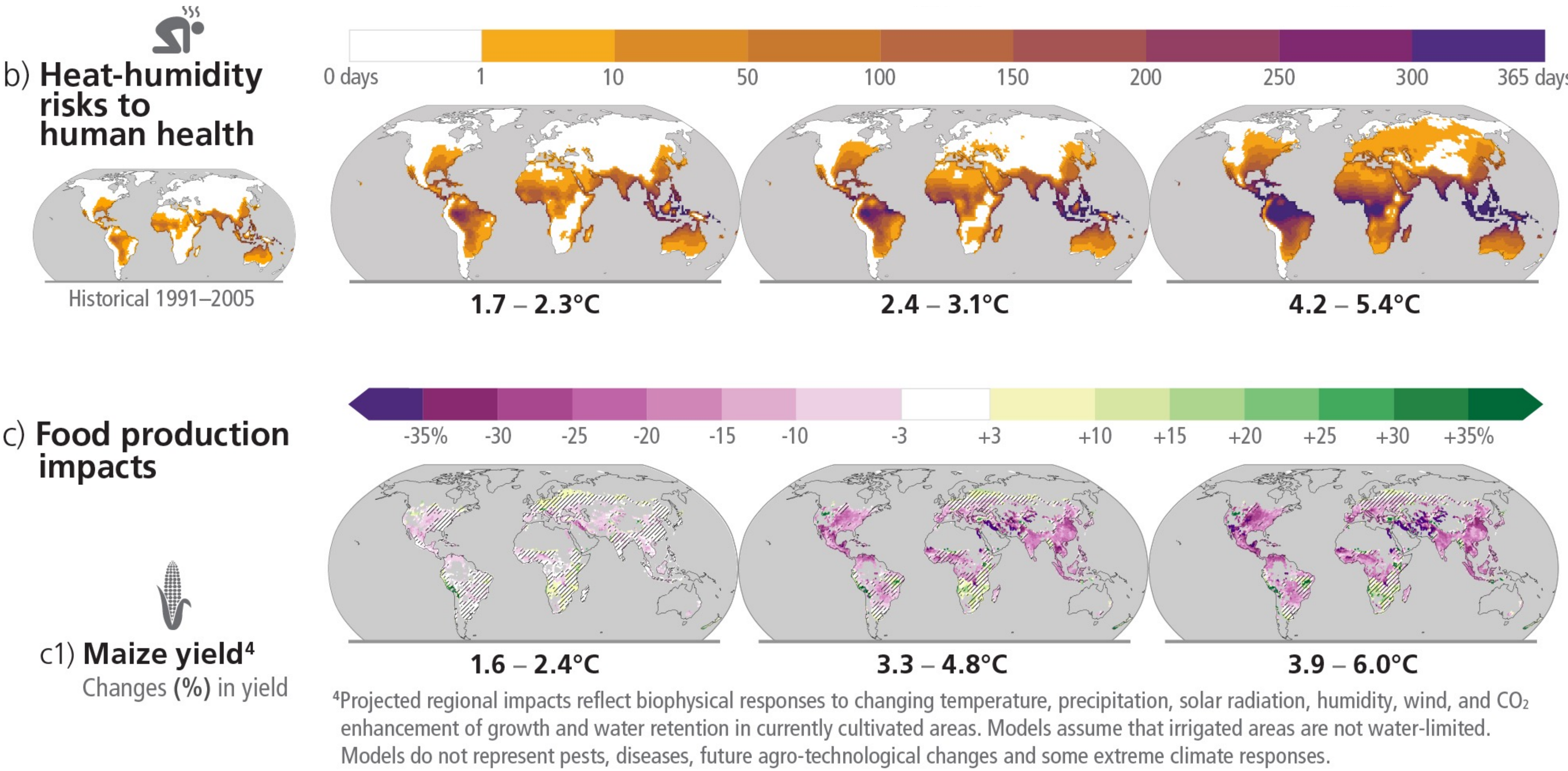
Motivation

- Why is 2°C or above tragic?



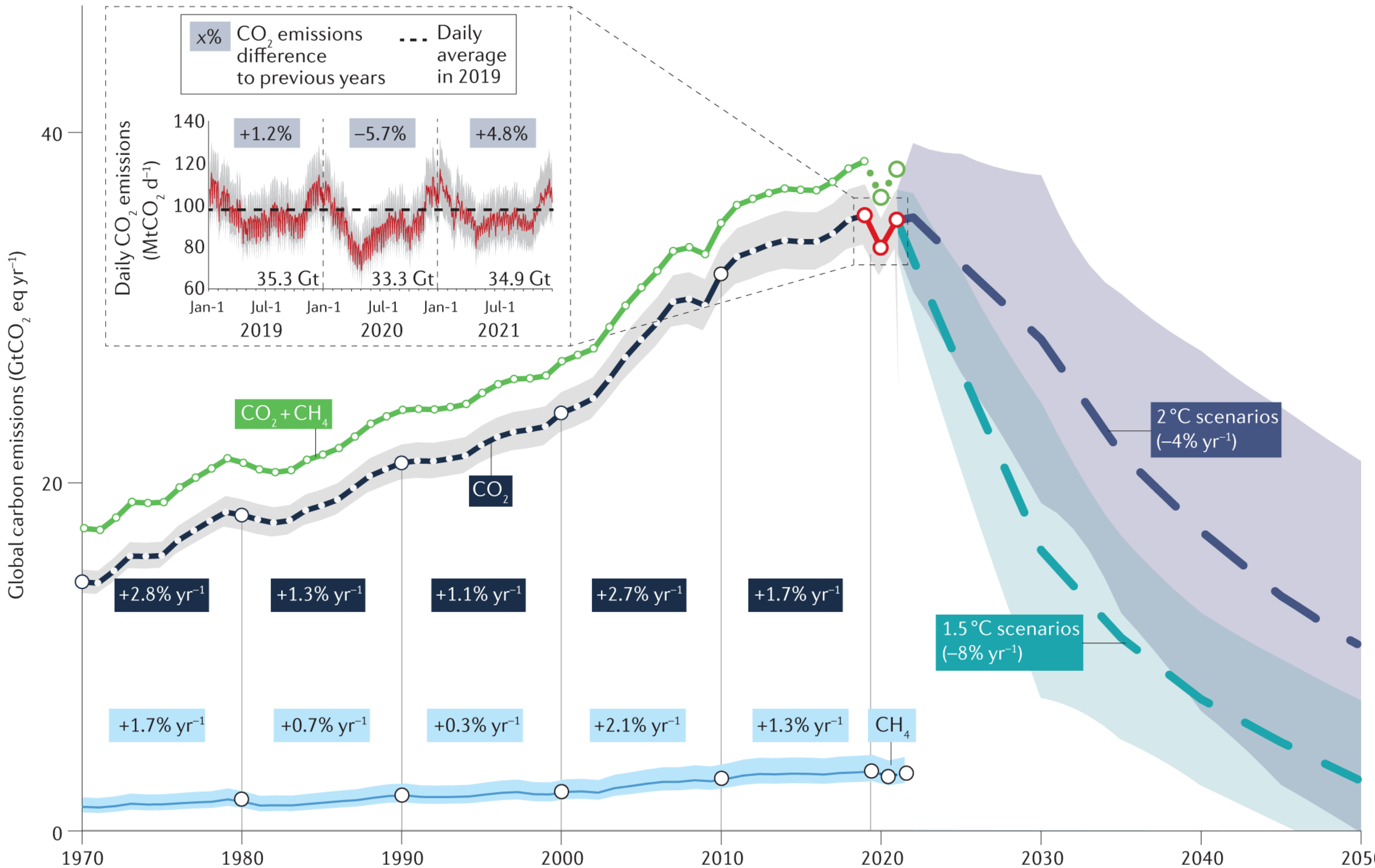
IPCC, 2023

Motivation



IPCC, 2023

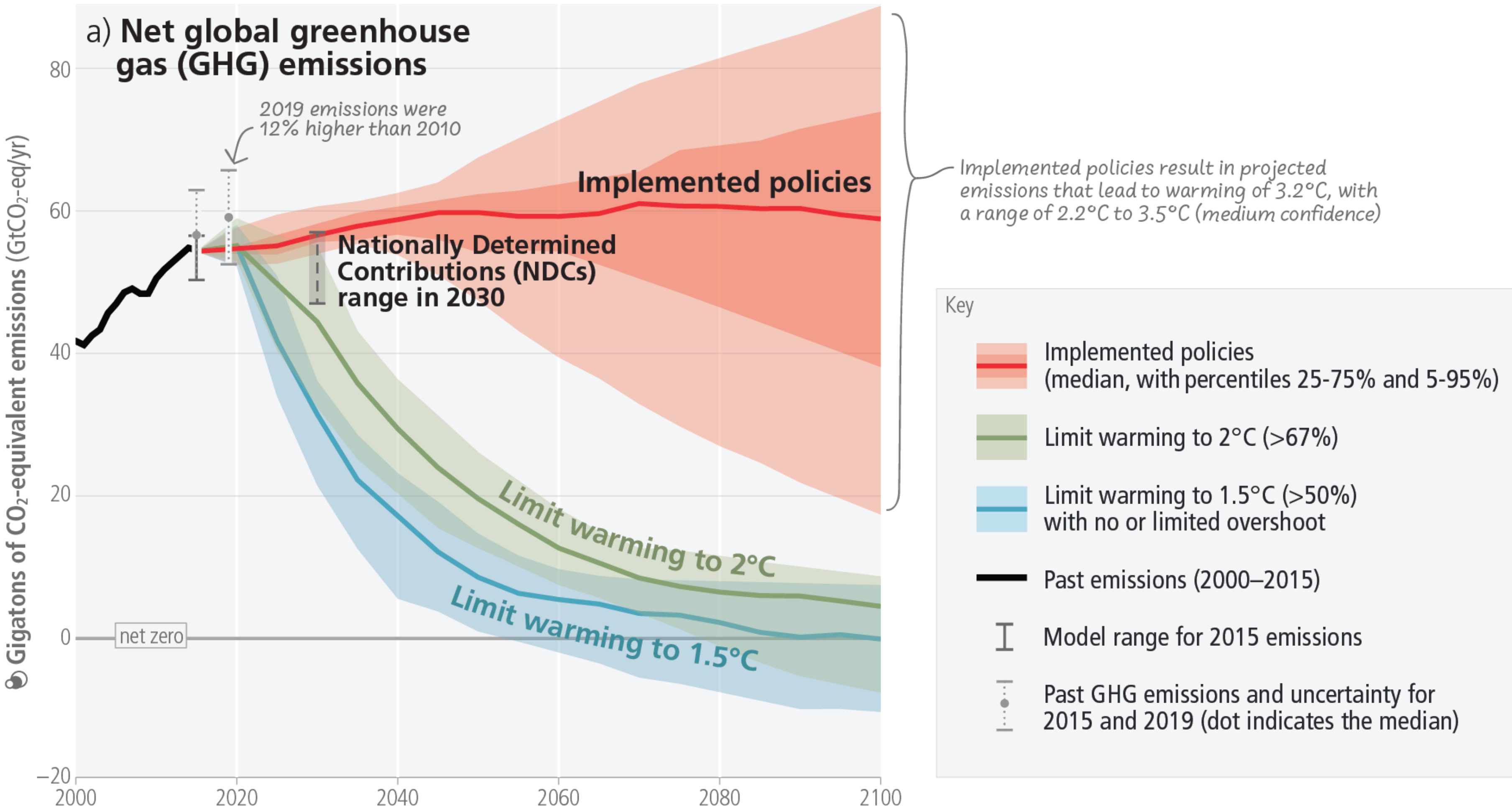
Motivation



Liu, Zhu, et al. "Monitoring global carbon emissions in 2021." *Nature Reviews Earth & Environment* 3.4 (2022): 217-219.

- Limiting warming to 1.5 °C to 2°C involves **dramatic** reductions in GHG emissions

Motivation



IPCC, 2023

- Limiting warming to 1.5 °C to 2°C involves **dramatic** reductions in GHG emissions

Motivation

- However, international cooperation and policy are lagging behind
- “Orderly phase out of unabated fossil fuel” → “Transition away from fossil fuel”

The Guardian

Cop28 draft climate deal criticised as ‘grossly insufficient’ and ‘incoherent’

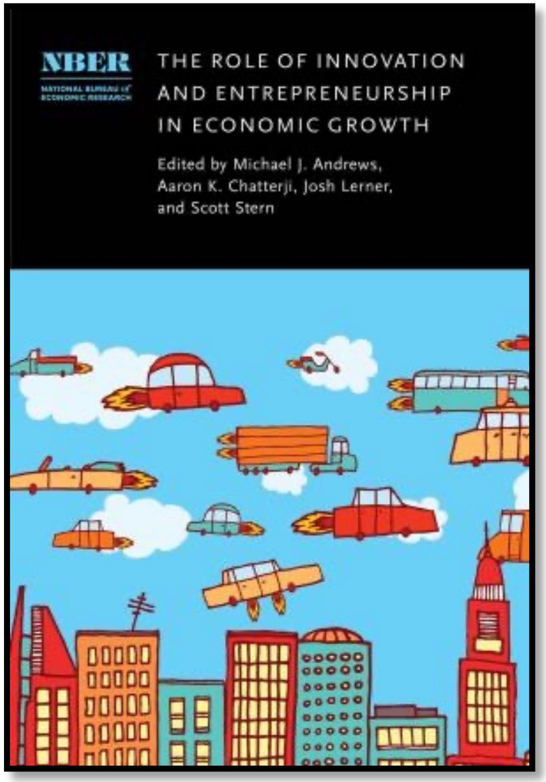
Text now being considered by governments calls for ‘reducing both consumption and production of fossil fuels’

The text avoids highly contentious calls for a “phase-out” or “phase-down” of fossil fuels, which have been the focus of deep disagreement among the more than 190 countries meeting in Dubai.

But instead of requiring fossil fuel producers to cut their output, it frames such reductions as optional, by calling on countries to “take actions that could include” reducing fossil fuels. “That one word ‘could’ just kills

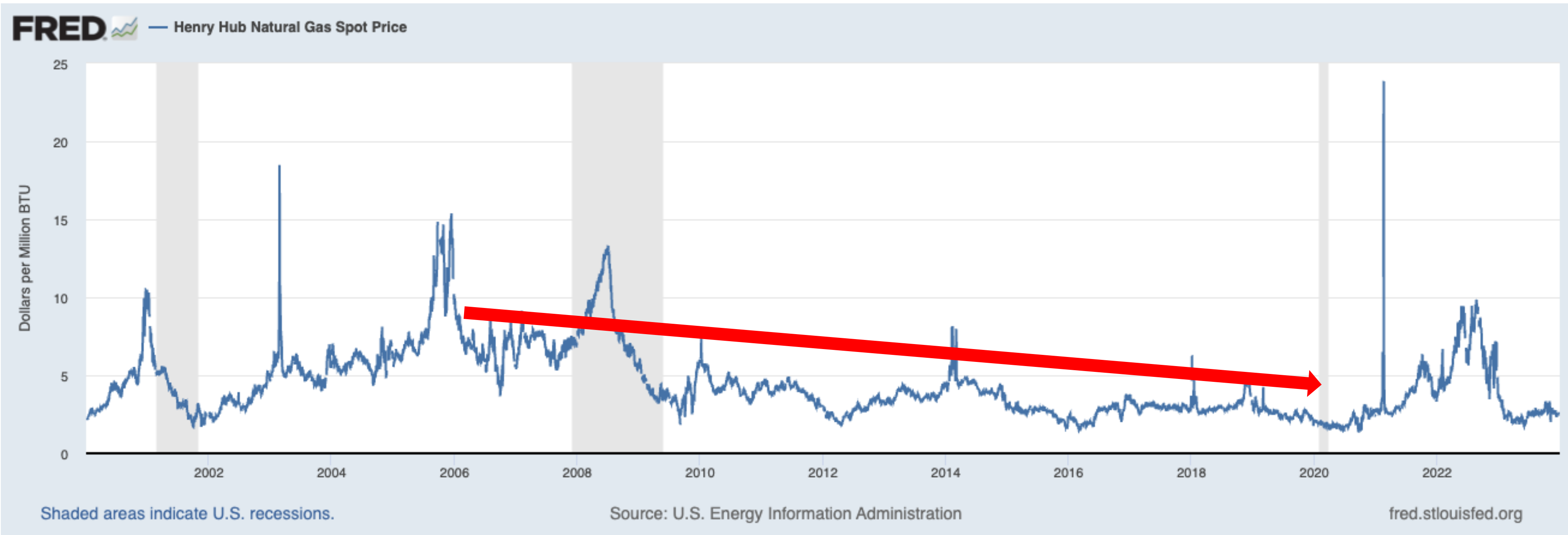
Motivation

- Researchers argue that **technological innovation** is one of the most promising instruments through which firms can tackle climate change
  - Popp et al. (2020), "Innovation and entrepreneurship in the energy sector." *National Bureau of Economic Research*
- Policy makers are also interested
  - Jake Sullivan, Security advisor, White house
    1. Computing-related technologies
    2. Bio-technologies
    3. Clean energy technologies



Background

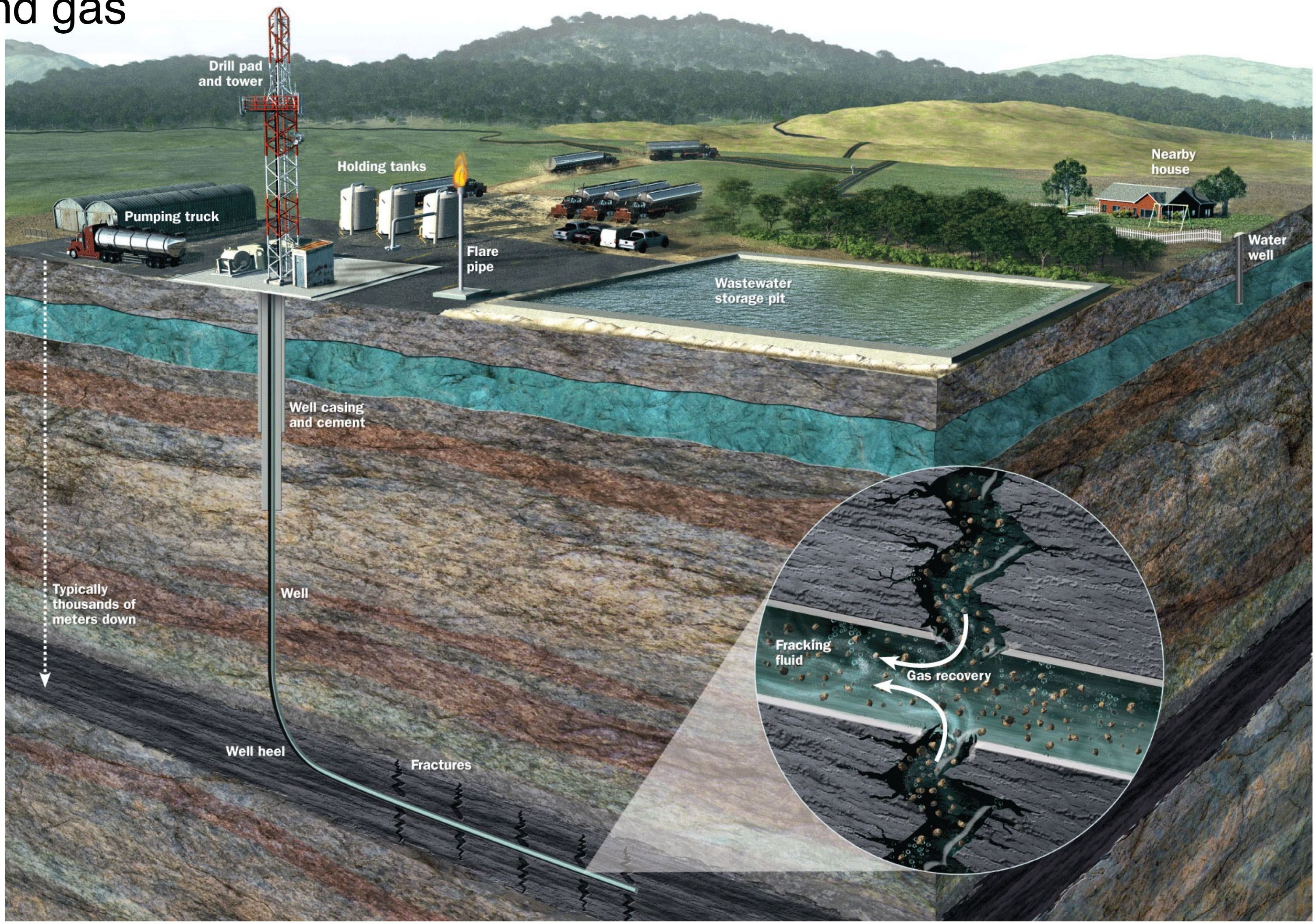
- But then, is there enough incentive to invest in green technology?



  – The Shale boom created a downward pressure in oil and gas prices

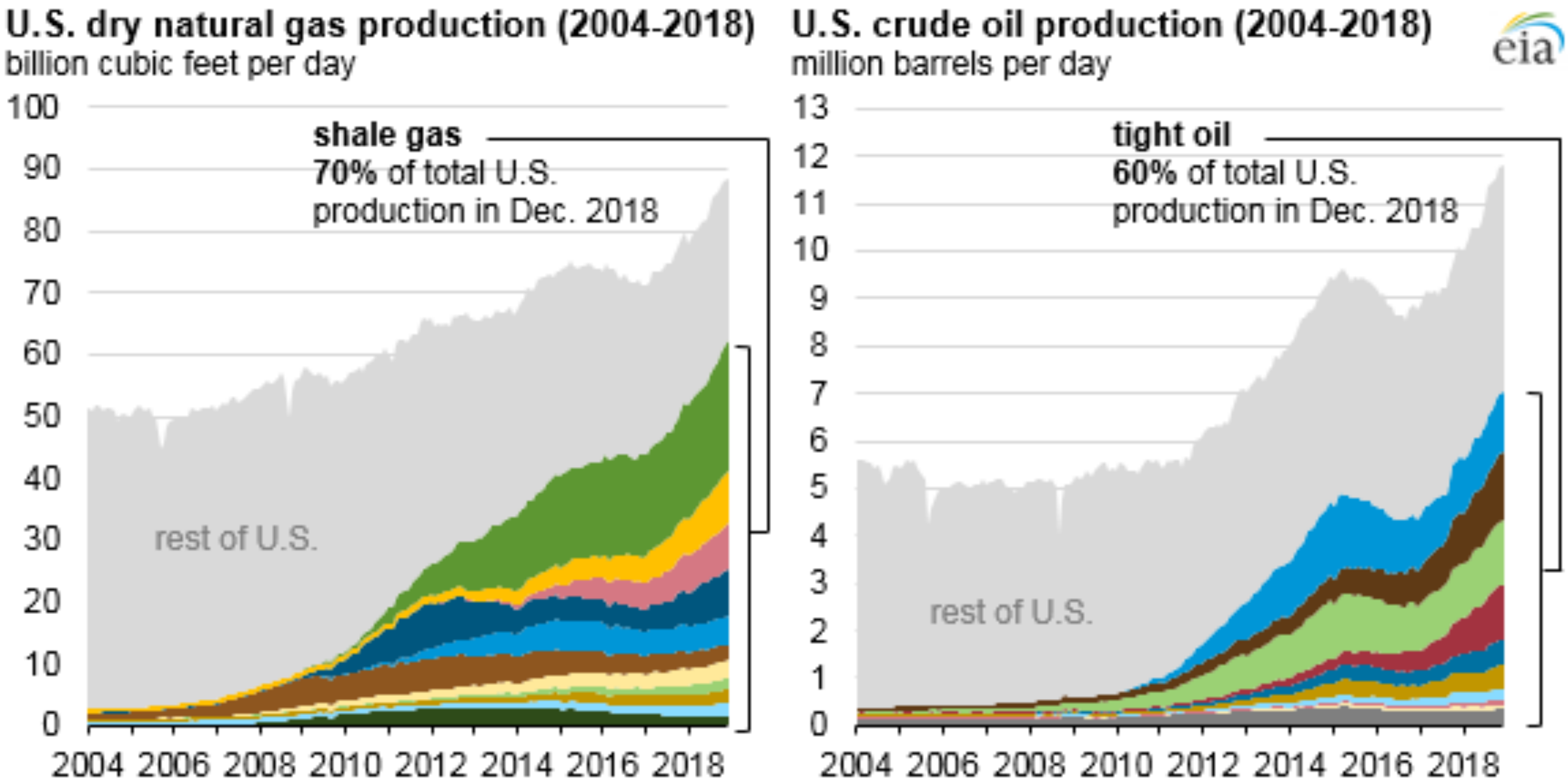
Background

- Horizontal drilling and hydraulic fracking opened the era of shale oil and gas

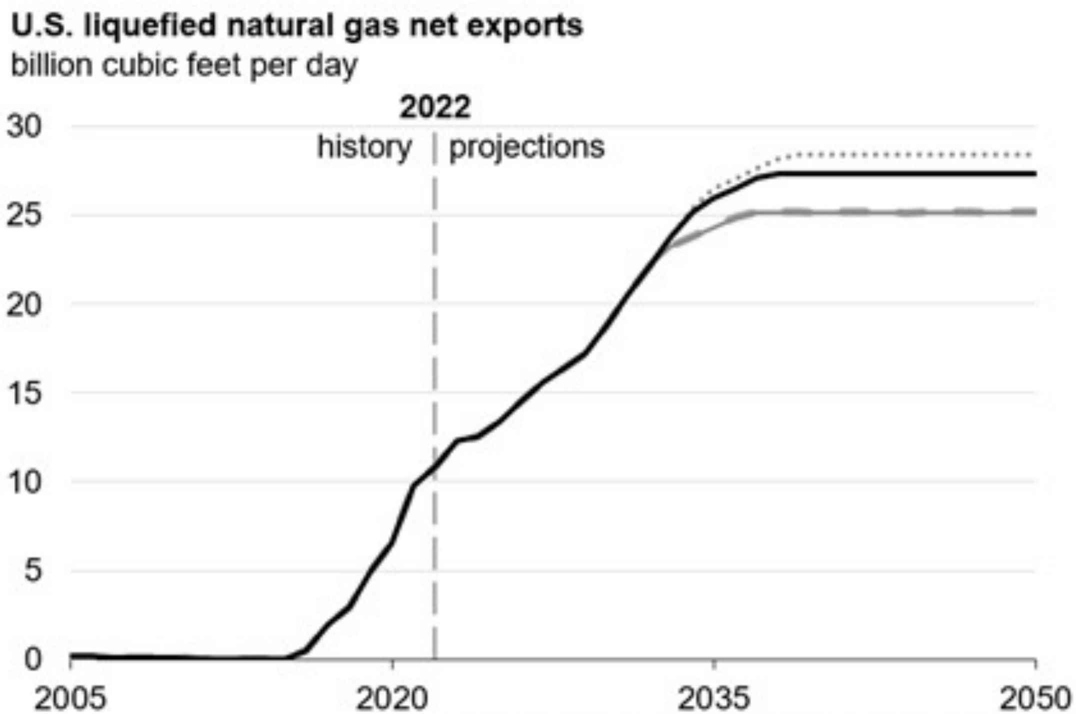


Background

- The development of Shale fields led to the boom of oil and gas production

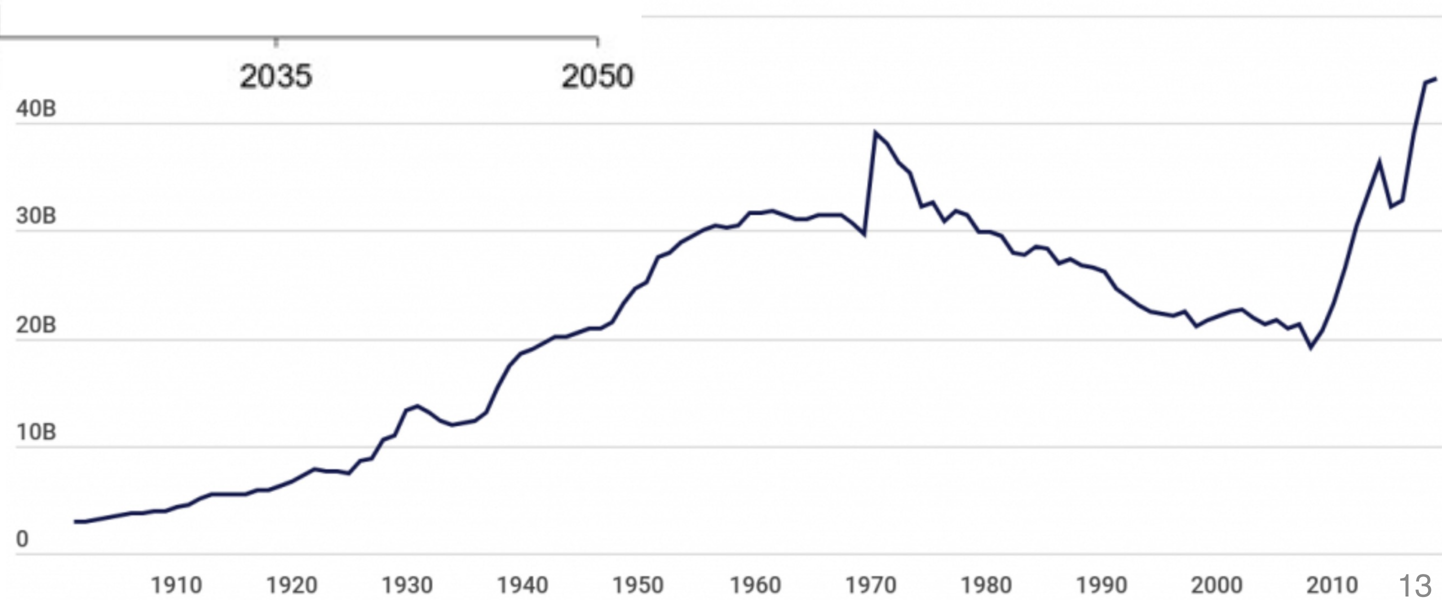


Background



Source: EIA

Proven oil reserves (barrels)

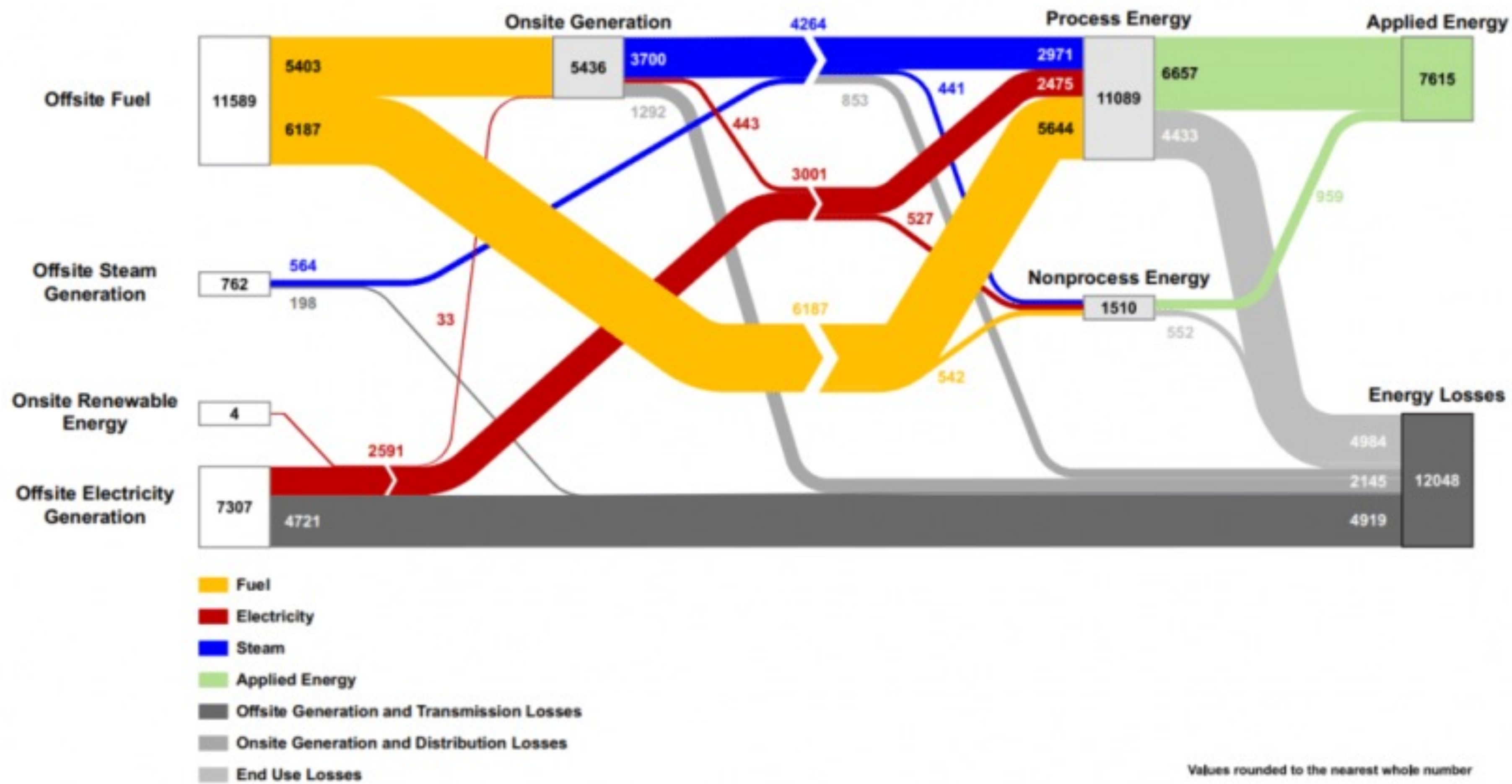


Background

- The Shale boom's economic prosperity came at the expense of the environment
  - Min (2020) finds that mining employment shocked by the shale boom reduced support for environmental policies
  - Acemoglu et al. (2023)
    - Short run: the Shale boom reduces carbon emissions by inducing substitution away from coal
    - Long run: the Shale boom discourages clean energy innovation of the energy sector
- What about the industrial sector that is responsible for 40% of global GHG emissions?

Background

- The industrial sector does not rely on oil and gas entirely
- Depending on whether cheap oil and gas can substitute the existing input, investment into green R&D will decrease or increase



Research Question

- Does the U.S. shale boom impact the green innovation of non-energy firms?
- What types of green innovation are affected by the shale boom?
- What mechanisms led to the adjustment of corporate green innovation upon the shale boom?

Theoretical Predictions

- We formalize our idea that "depending on whether cheap oil and gas can substitute the existing input, investment into green R&D will decrease or increase"
- Define a representatitive firm's profit maximization as:

$$\max_{\{C,G,R_C,R_G\}} p_Y Y(C,G,R_C,R_G) - c_C R_C - c_G R_G - p_C C - p_G G$$

where $Y = \left(\lambda_C R_C^{\beta} C^{\rho} + \lambda_G R_G^{\beta} G^{\rho}\right)^{\frac{1}{\rho}}$ and $A_s = \lambda_s (R_s)^{\beta}\ \forall s = C,G$

  – Similar to Acemoglu (2003) "Skill premia" framework

- $R_s\ \forall s = C,G$ denotes R&D, C denotes convential energy, G denotes green energy
- FOC's yield: $\frac{\partial\ log\left(\frac{R_C}{R_G}\right)}{\partial\ log\left(\frac{p_C}{p_G}\right)} = -\frac{\rho}{1-\rho-\beta}$
- We can show the sign depends on ρ: substitubaility between C and G

Emprical Findings

- Does the U.S. shale boom impact the green innovation of non-energy firms?
- What types of green innovation are affected by the shale boom?
  - **Green production ↓**
  - **Green transportation, green infrastructure not affected**

- What mechanisms led to the adjustment of corporate green innovation upon the shale boom?
  - **“Green production ↓” is more salient for goods producers, energy-intensive firms, and oil & gas dependent firms**

Literature Review

- Many factors influence corporate green innovation
  - (i) external environments and market conditions
    - Market competition, size: Bansal and Roth (2000), Wang et al. (2021), Noailly and Ryfisch (2015)
    - Consumer pressure: Popp (2019)
    - Energy prices: Acemoglu et al. (2023)
  - (ii) corporate governance
    - El-Kassar and Singh (2019), Amore and Bennedsen (2016), He and Jiang (2019)
  - (iii) public policies and regulations
    - Aguilera-Caracuel and Ortiz-de-Mandojana (2013), Brunnermeier and Cohen (2003), Weng et al. (2015), Fabrizi et al. (2018), Kesidou and Wu (2020), Krass et al. (2013)

Theory Model

- Define a representative firm's profit maximization as:

$$\max_{\{C,G,R_C,R_G\}} p_Y Y(C, G, R_C, R_G) - c_C R_C - c_G R_G - p_C C - p_G G$$

where $Y = \left(\lambda_C R_C^{\beta} C^{\rho} + \lambda_G R_G^{\beta} G^{\rho}\right)^{\frac{1}{\rho}}$ and $A_s = \lambda_s (R_s)^{\beta}\ \forall s = C, G$

- R_s denotes R&D, C denotes convential energy, G denotes green energy
- Note that CRS implies that $\beta + \rho < 1$
- Note that we assume that the price of input energy p_s are exogenous, implying that non-energy firms are not large enough to affect energy input prices
- Also, c_s are exogenous, implying that labor market is competitive and reponsive

Theory Model

- FOC's yield: $\frac{\partial\, log\left(\frac{R_C}{R_G}\right)}{\partial\, log\left(\frac{p_C}{p_G}\right)} = -\frac{\rho}{1-\rho-\beta}$
- In a CES function, ρ specifies the substitutability between the inputs, C and G
  - Substitute: $\rho > 0$; complement: $\rho < 0$
- If C and G are substitutes, $\rho > 0 \Rightarrow -\left(\frac{\rho}{1-\rho}\right) < 0 \Rightarrow -\frac{\rho}{1-\rho-\beta} < 0$

$$\Rightarrow \frac{\partial\, log\left(\frac{R_C}{R_G}\right)}{\partial\, log\left(\frac{p_C}{p_G}\right)} < 0$$

- If $\frac{p_C}{p_G}\downarrow$, then the firm wants $\frac{C}{G}\uparrow$ (i.e., use more C relative to G). Since input substitution is flexible (i.e, $\sigma > 1$), an increase in $\frac{C}{G}$ yields more Y. Since productivities augment yields, the firm wants higher productivity from C (i.e., $\frac{A_C}{A_G}\uparrow \Rightarrow \frac{R_C}{R_G}\uparrow$)
- If C and G are complements, an increase in $\frac{C}{G}$ does not yield more Y. Then, the firm wants higher productivity from G

Data

- USPTO (US Patent and Trademark Office)
- 2000 ~ 2016
  - Obtained through 2019 but restricted to 2016 due to the right-censorship
  - Median lag in patent granting is 2.9 years
- Cooperative Patent Classification (CPC) class of Y
  - a dedicated classification scheme for climate change-related technologies

Data

- Operation-oriented green innovation
  - green production (Y02P)
  - green transportation (Y02T)
  - green infrastructure
    - green building (Y02B)
    - green information and communication technology (ICT) equipment (Y02D)
- Non-operation-oriented green innovation (i.e., direct climate change mitigation)
  - adaptation to climate change (Y02A)
  - pollutant management (e.g., capture and storage of GHGs and waste management) (Y02C and Y02W)
  - green energy (e.g., renewable energy and smart grid) (Y02E and Y04S).

Data

- Green production (Y02P)

CPC	COOPERATIVE PATENT CLASSIFICATION
Y02P	CLIMATE CHANGE MITIGATION TECHNOLOGIES IN THE PRODUCTION OR PROCESSING OF GOODS

NOTE

This subclass covers climate change mitigation technologies in any kind of industrial processing or production activity, including the agroalimentary industry, agriculture, fishing, ranching and the like.

+	Y02P 10/00	Technologies related to metal processing
+	Y02P 20/00	Technologies relating to chemical industry
+	Y02P 30/00	Technologies relating to oil refining and petrochemical industry
+	Y02P 40/00	Technologies relating to the processing of minerals
+	Y02P 60/00	Technologies relating to agriculture, livestock or agroalimentary industries
+	Y02P 70/00	Climate change mitigation technologies in the production process for final industrial or consumer products
+	Y02P 80/00	Climate change mitigation technologies for sector-wide applications
+	Y02P 90/00	Enabling technologies with a potential contribution to greenhouse gas [GHG] emissions mitigation

Data

- Green production (Y02P)

CPC	COOPERATIVE PATENT CLASSIFICATION
Y02P	CLIMATE CHANGE MITIGATION TECHNOLOGIES IN THE

NOTE

This subclass covers climate change mitigation techn
production activity, including the agroalimentary indus

+	**Y02P 10/00**	**Technologies related to metal processing**
-	**Y02P 20/00**	**Technologies relating to chemical industry**
-	Y02P 20/10	. Process efficiency
	Y02P 20/129	. . Energy recovery, e.g. by cogeneration, H_2recovery or pre
	Y02P 20/133	. . Renewable energy sources, e.g. sunlight
-	Y02P 20/141	. Feedstock
	Y02P 20/143	. . the feedstock being recycled material, e.g. plastics
	Y02P 20/145	. . the feedstock being materials of biological origin
-	Y02P 20/151	. Reduction of greenhouse gas [GHG] emissions, e.g. CO_2
	Y02P 20/155	. . Perfluorocarbons [PFC]; Hydrofluorocarbons [HFC]; Hydr [CFC]
	Y02P 20/156	. . Methane [CH_4]
	Y02P 20/20	. Improvements relating to chlorine production
	Y02P 20/30	. Improvements relating to adipic acid or caprolactam produ
	Y02P 20/40	. Improvements relating to fluorochloro hydrocarbon, e.g. ch
-	Y02P 20/50	. Improvements relating to the production of bulk chemicals
	Y02P 20/52	. . using catalysts, e.g. selective catalysts
	Y02P 20/54	. . using solvents, e.g. supercritical solvents or ionic liquids
	Y02P 20/55	. . Design of synthesis routes, e.g. reducing the use of auxiliary or protecting groups
	Y02P 20/582	. . Recycling of unreacted starting or intermediate materials
	Y02P 20/584	. . Recycling of catalysts
	Y02P 20/59	. . Biological synthesis; Biological purification
+	**Y02P 30/00**	**Technologies relating to oil refining and petrochemical industry**

US010472338B2

(12) **United States Patent**
Okumura et al.

(10) **Patent No.: US 10,472,338 B2**
(45) **Date of Patent: Nov. 12, 2019**

(54) **METHOD FOR PRODUCING [^{18}F]FLUTEMETAMOL**

(71) Applicants: **GE Healthcare Limited**, Buckinghamshire (GB); **Nihon Medi-Physics Co., Ltd.**, Tokyo (JP)

(72) Inventors: **Yuki Okumura**, Tokyo (JP); **Gota Tonoya**, Tokyo (JP); **Tomoyuki Matsunami**, Tokyo (JP)

(73) Assignees: **GE HEALTHCARE LIMITED**, Buckinghamshire (GB); **NIHON MEDI-PHYSICS CO., LTD.**, Tokyo (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/764,309**

(22) PCT Filed: **Oct. 17, 2016**

(86) PCT No.: **PCT/EP2016/074840**
§ 371 (c)(1),
(2) Date: **Mar. 28, 2018**

(87) PCT Pub. No.: **WO2017/071980**
PCT Pub. Date: **May 4, 2017**

(65) **Prior Publication Data**
US 2019/0055207 A1 Feb. 21, 2019

(30) **Foreign Application Priority Data**
Oct. 28, 2015 (JP) 2015-211413

(51) **Int. Cl.**
C07D 277/66 (2006.01)

(52) **U.S. Cl.**
CPC ***C07D 277/66*** (2013.01); *Y02P 20/55* (2015.11)

(58) **Field of Classification Search**
CPC C07D 277/66
See application file for complete search history.

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International Search Report and the Written Opinion of the International Searching Authority, or the Declaration from International Appl. No. PCT/EP2016/074840, dated Nov. 28, 2016.

* cited by examiner

Primary Examiner — Golam M Shameem
(74) *Attorney, Agent, or Firm* — Arent Fox LLP

(57) **ABSTRACT**

Provided is a method for producing flutemetamol including the steps of: reacting a precursor compound represented by a predetermined general formula with a radioactive fluoride to obtain a ^{18}F labeling compound represented by a predetermined general formula; allowing a strong base to act on the reaction mixture of the above step containing the precursor compound and the ^{18}F labeling compound; after the above step, purifying the ^{18}F labeling compound using a reverse phase solid phase extraction cartridge; and removing a protective group to obtain [^{18}F]flutemetamol.

20 Claims, No Drawings

Data

- Green transportation (Y02T)

	CPC	COOPERATIVE PATENT CLASSIFICATION
	Y02T	CLIMATE CHANGE MITIGATION TECHNOLOGIES RELATED TO TRANSPORTATION
+	Y02T 10/00	Road transport of goods or passengers
	Y02T 30/00	Transportation of goods or passengers via railways, e.g. energy recovery or reducing air resistance
+	Y02T 50/00	Aeronautics or air transport
+	Y02T 70/00	Maritime or waterways transport
+	Y02T 90/00	Enabling technologies or technologies with a potential or indirect contribution to GHG emissions mitigation

- Green infrastructure (Building: Y02B; ICT equipment: Y02D)

	CPC	COOPERATIVE PATENT CLASSIFICATION
	Y02B	CLIMATE CHANGE MITIGATION TECHNOLOGIES RELATED TO BUILDINGS, e.g. HOUSING, HOUSE APPLIANCES OR RELATED END-USER APPLICATIONS
+	Y02B 10/00	Integration of renewable energy sources in buildings
+	Y02B 20/00	Energy efficient lighting technologies, e.g. halogen lamps or gas discharge lamps
+	Y02B 30/00	Energy efficient heating, ventilation or air conditioning [HVAC]
+	Y02B 40/00	Technologies aiming at improving ... technologies for refrigerators, free...
	Y02B 50/00	Energy efficient technologies in el... recuperation technologies
+	Y02B 70/00	Technologies for an efficient end-...
+	Y02B 80/00	Architectural or constructional ele...
+	Y02B 90/00	Enabling technologies or technolo... mitigation

	CPC	COOPERATIVE PATENT CLASSIFICATION
	Y02D	CLIMATE CHANGE MITIGATION TECHNOLOGIES IN INFORMATION AND COMMUNICATION TECHNOLOGIES [ICT], I.E. INFORMATION AND COMMUNICATION TECHNOLOGIES AIMING AT THE REDUCTION OF THEIR OWN ENERGY USE

NOTES

1. This subclass covers information and communication technologies [ICT] whose purpose is to minimize the use of energy during the operation of the involved ICT equipment.
2. This subclass does not cover the use of an ICT technology supporting energy efficient operation of a further piece of equipment, nor the reuse or recycling of ICT equipment.

	CPC	Description
	Y02D 10/00	Energy efficient computing, e.g. low power processors, power management or thermal management
+	Y02D 30/00	Reducing energy consumption in communication networks

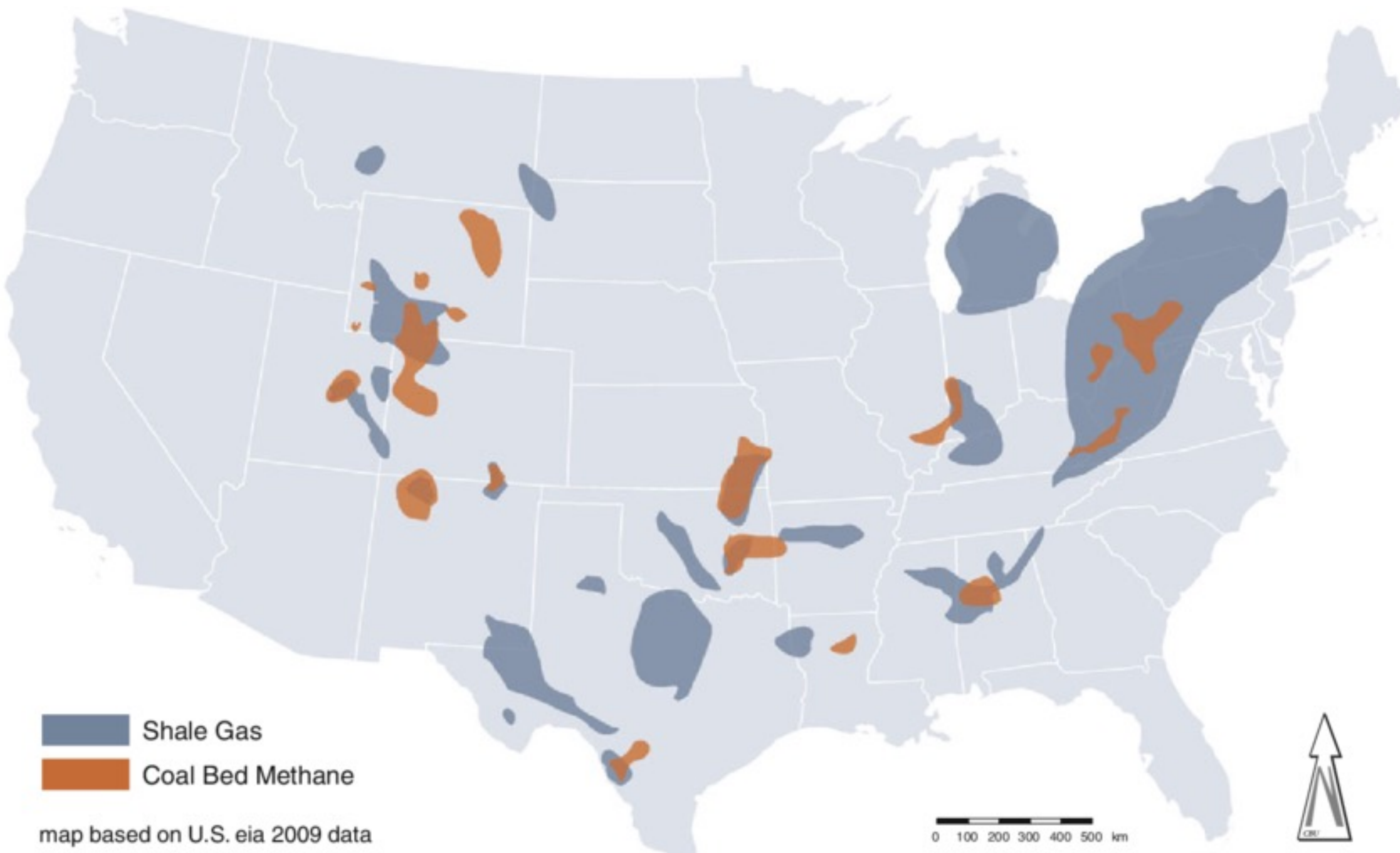
Data

- Compustat: firm characteristics
  - Firm profitability and size: ROA, ROE, net sales
  - Innovation capability: R&D expenditure
  - Firm location: headquarters
- Sample restriction
  - 1,303 non-energy firms that operated between 2002 and 2016
  - Account for 70% of all patents during the sample period
  - Operation-oriented green innovation: 86.3% of the green patent stock.
    - production (20.2%), transportation (32.2%), and infrastructure (33.9%)

Variable	Mean	Std. Dev.	Description	Source
Dependent Variables				
Green Patent Stock	7.200	56.909	Cumulative counts (stock) of patents applied (and eventually granted) for CPC c lass of Y, dedicated to climate change mitigation and adaptation technologies	USPTO
Operation-Oriented Green Innovation				
Green Production	1.456	11.152	Patent stock for CPC class of Y02P (green production and processing of goods)	USPTO
Green Transportation	2.320	37.145	Patent stock for CPC class of Y02T (green transportation)	
Green Infrastructure	2.437	29.668	Patent stock for CPC classes of Y02B (green building) and Y02D (green ICT eq uipment)	USPTO
Non-operation-Oriented Green Innovation				
Climate Change Adaptation	0.412	2.957	Patent stock for CPC class of Y02A	USPTO
Pollutant Management	0.218	1.984	Patent stock for CPC classes of Y02C (capture or disposal of greenhouse gases) and Y02W (wastewater and solid waste management)	USPTO
Green Energy	0.959	8.508	Patent stock CPC classes of Y02E (green energy generation, transmission, or dis tribution) and Y04S (smart grids)	USPTO
Independent Variable				
State-Level Shale Boom	0.255	0.436	Dichotomous indicator of shale-booming states, based on oil and gas production and employment in the state of a company's headquarters	Weinstein (2014)
County-Level Shale Boom	0.222	0.415	Alternative measure of shale boom, indicating the year and afterward when the c ounty of a company's headquarters experienced at least 10% of annual growth i n employment in the gas and oil sector	CBP
Shale Well-Based Shale Boom	0.135	0.342	Alternative measure of shale boom, indicating whether the county within a 100-mile radius of a company's headquarters went into the shale boom defined by th e top quintile of the number of shale wells	Gilje (2019)
Control Variables				
Return on Assets	-0.230	1.807	Net income per total assets	Compustat
Return on Equity	-0.115	0.998	Net income per shareholders' equity	Compustat
Sales	5,138.42	14,424.38	Net sales	Compustat
R&D Stock	542.725	2,857.892	Cumulative R&D expenses (stock)	Compustat
Nongreen Patent Stock	121.232	822.255	Cumulative counts (stock) of all patents applied (and eventually granted)	USPTO
Industry Green Patent Stock	7.200	23.507	Average green patent stock in the same industry at 4-digit NAICS level	USPTO
Industry Concentration	0.190	0.156	Herfindahl-Hirschman Index (HHI) of sales in the same industry at 4-digit NAI CS level	Compustat

Research Design

- Geographic variation of the shale bed location creates variations in local energy markets



Research Design

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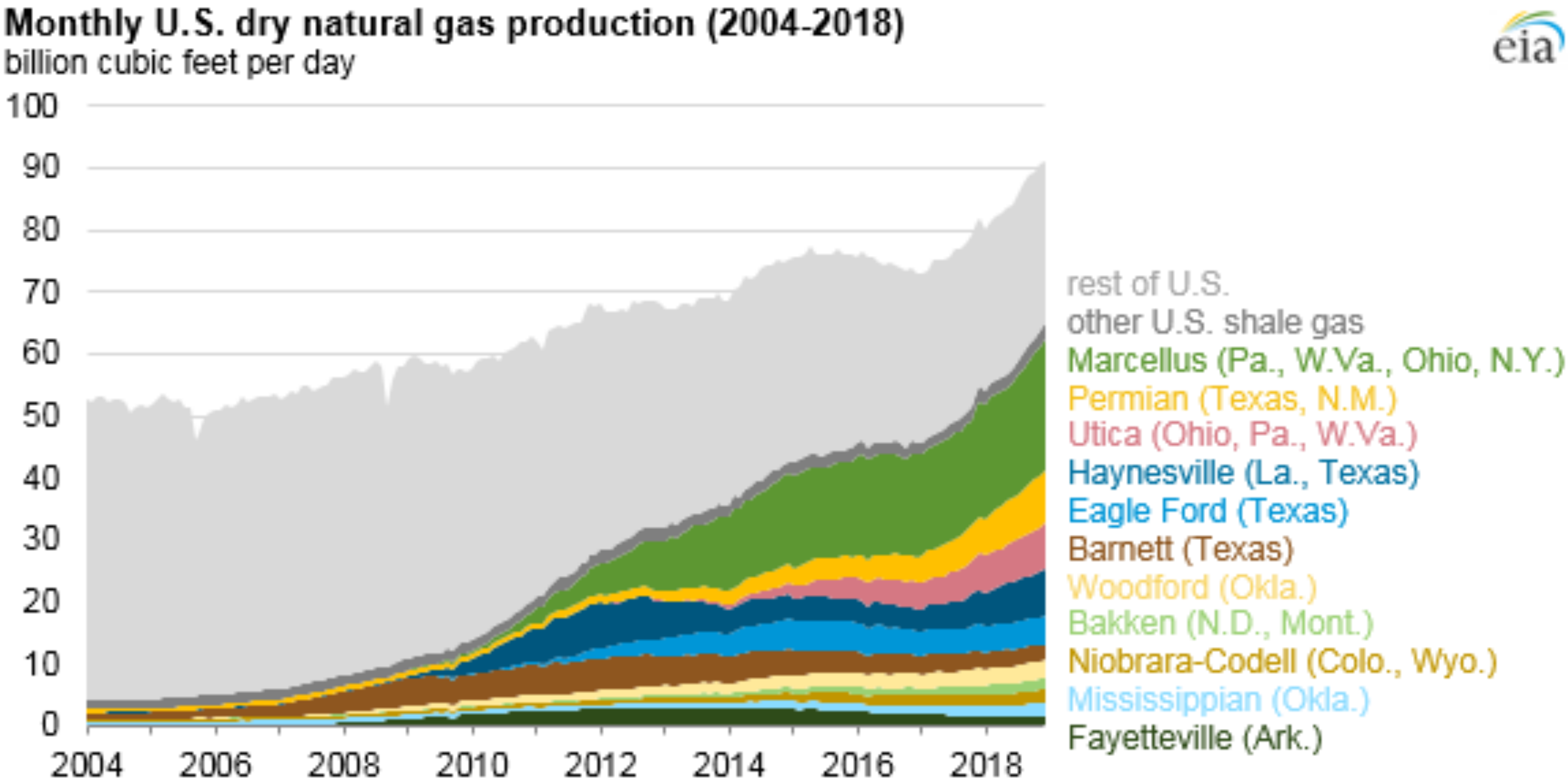


Research Design

- **Treatment**: firms headquartered in the shale-booming states
- **Control**: firms headquartered outside of the shale-booming states

- Prior literature leverages similar variation but at county-level treatment
  – Weinstein (2014), Muehlenbachs et al. (2015), Gilje (2019); Wu and Jiang (2022)
- State-level treatment is more relevant in our setting
  – Firms are not located in immediate proximity to shale wells
  – The Shale boom affects the local economy well beyond the county level (Feyrer et al. 2017)

Difference-in-Differences Estimator

$$Patent\ Stock_{it+1} = +\beta Shale\ Boom_{it} + \gamma Control_{it+1} + \theta_i + \mu_t + \varepsilon_{it}$$

- Controls
  - firm characteristics, including (i) sales that approximate firm size, (ii) profitability, (iii) non-green patent stock (all patents less than green patents) and R&D stock that account for a firm's general capabilities and investments in innovation activities, and (iv) industry green patents and industry concentration
  - Firm and time FE

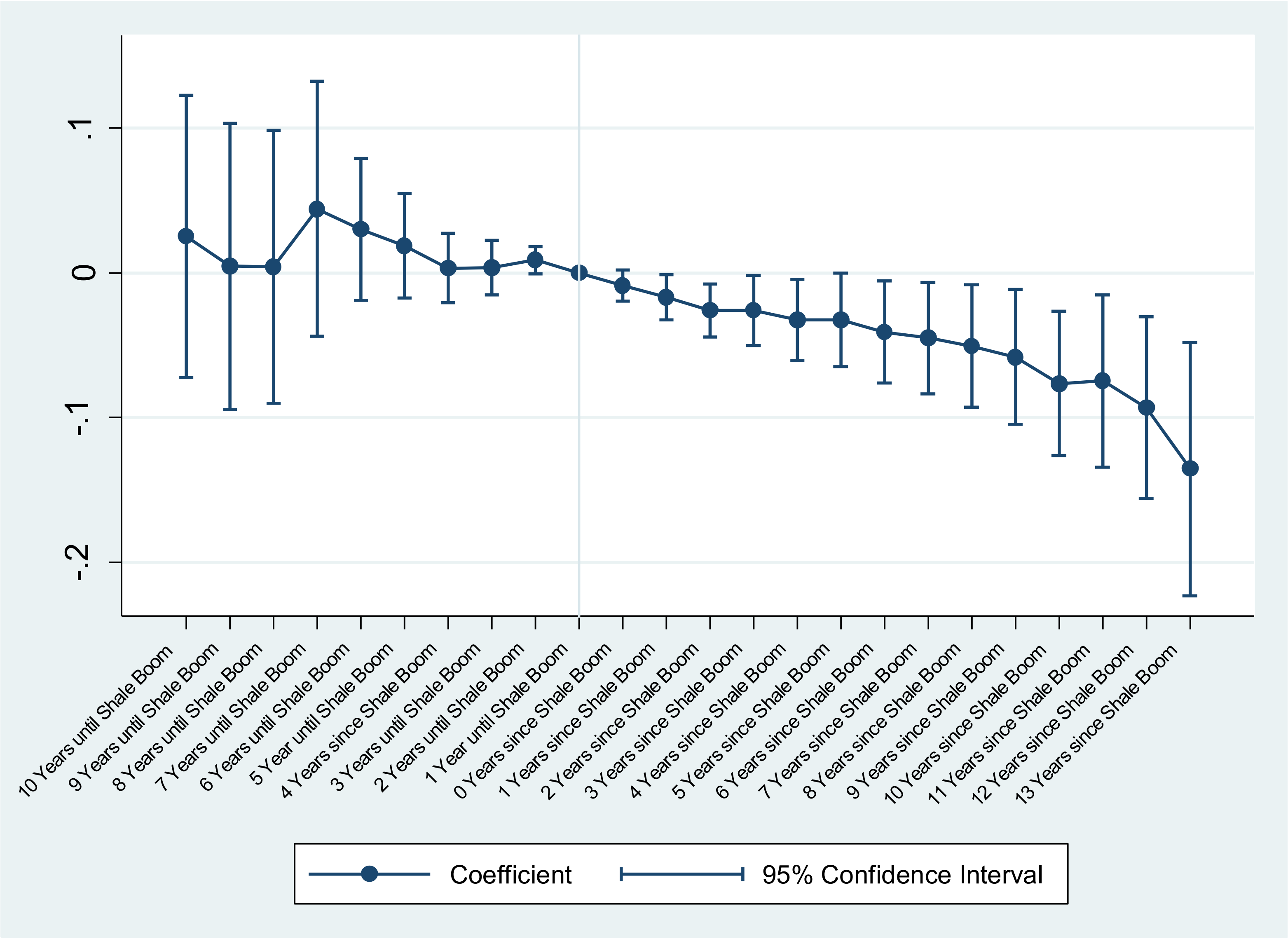
Matching

	Balance Check		
	Before Matching		
	Treatment Group	Control Group	
	Mean	Mean	Mean diff
	(1)	(2)	(3)
Return on Assets	-0.369	-0.233	-0.136
Return on Equity	-0.201	-0.130	-0.071
ln(Sales)	5.731	5.298	0.433***
ln(R&D Stock)	1.802	2.647	-0.845***
ln(Patent Stock)	1.476	1.850	-0.374***
Industry Concentration	0.181	0.162	0.019**
Energy Intensity	0.083	0.066	0.017***
NAICS 31	0.047	0.028	0.019*
NAICS 32	0.187	0.199	-0.012
NAICS 33 (Manufacturing)	0.308	0.430	-0.122***
NAICS 42 (Wholesale trade)	0.056	0.019	0.037***
NAICS 44	0.009	0.018	-0.009
NAICS 45	0.019	0.011	0.008
NAICS 48	0.026	0.013	0.013
NAICS 49	0.002	0.001	0.001
NAICS 51	0.094	0.093	0.001
NAICS 52 (Finance and insurance)	0.109	0.050	0.059***
NAICS 53	0.015	0.032	-0.017*
NAICS 54	0.047	0.041	0.006
NAICS 56	0.021	0.024	-0.003
NAICS 61	0.004	0.002	0.002
NAICS 62	0.024	0.015	0.009
NAICS 71	0.006	0.004	0.002
NAICS 72	0.006	0.013	-0.007
NAICS 81	0.006	0.002	0.004
Number of Firms	468	835	

Balance-of-Covariates

	Treatment Group	Control Group	
	Mean	Mean	Mean diff
	(4)	(5)	(6)
Return on Assets	-0.296	-0.297	0.001
Return on Equity	-0.194	-0.183	-0.011
ln(Sales)	5.736	5.854	-0.118
ln(R&D Stock)	1.809	1.870	-0.061
ln(Patent Stock)	1.481	1.535	-0.054
Industry Concentration	0.179	0.180	-0.001
Energy Intensity	0.082	0.090	-0.008
NAICS 31	0.047	0.060	-0.013
NAICS 32	0.188	0.166	0.022
NAICS 33	0.308	0.321	-0.013
NAICS 42	0.054	0.045	0.009
NAICS 44	0.009	0.011	-0.002
NAICS 45	0.019	0.015	0.004
NAICS 48	0.026	0.028	-0.002
NAICS 49	0.002	0.000	0.002
NAICS 51	0.095	0.086	0.009
NAICS 52	0.110	0.114	-0.004
NAICS 53	0.015	0.017	-0.002
NAICS 54	0.047	0.067	-0.020
NAICS 56	0.022	0.024	-0.002
NAICS 61	0.004	0.000	0.004
NAICS 62	0.022	0.026	-0.004
NAICS 71	0.006	0.002	0.004
NAICS 72	0.006	0.004	0.002
NAICS 81	0.006	0.002	0.004
Number of Firms	464	303	

Parallel Pre-trends



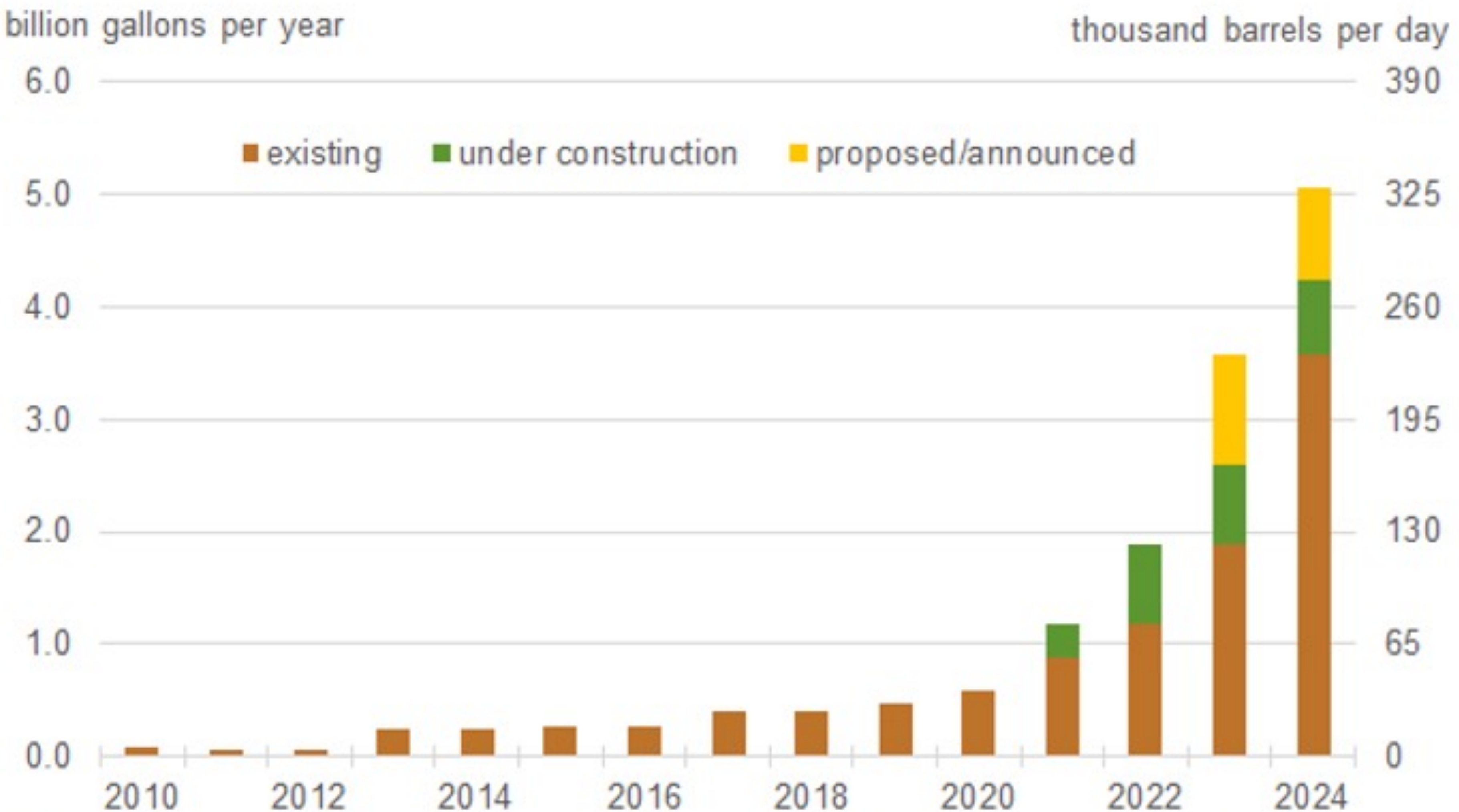
Regression Results

DV: ln(Patent Stock for Each Category)	Operation-Oriented Green Innovation		
	Green Production	Green Transportation	Green Infrastructure
	(1)	(2)	(3)
State-Level Shale Boom	**-0.040***** **(0.014)**	**-0.020** **(0.015)**	**-0.012** **(0.016)**
Return on Assets	-0.001* (0.001)	-0.001 (0.001)	-0.001 (0.001)
Return on Equity	-0.002 (0.002)	-0.001 (0.001)	-0.001 (0.002)
ln(Sales)	0.014** (0.006)	0.007 (0.005)	-0.000 (0.008)
ln(R&D Stock)	0.005 (0.012)	0.014* (0.008)	0.038*** (0.013)
ln(Nongreen Patent Stock)	0.074*** (0.012)	0.048*** (0.011)	0.072*** (0.015)
ln(Industry Green Patent Stock)	0.062** (0.025)	0.095*** (0.023)	0.213*** (0.042)
Industry Concentration	-0.011 (0.039)	-0.042 (0.040)	0.066 (0.046)
Firm Fixed Effects	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes
Within R-Squared	0.067	0.072	0.164
Number of Observations	12,272	12,272	12,272

- Negatively affects green production but not other types

Background

Figure 1: U.S. renewable diesel production capacity



Source: Graph by the U.S. Energy Information Administration, based on company announcements in trade press
Note: We assume proposed or announced projects are operational during stated year for capacity estimates.

Regression Results

	State Level Panel Data (2000 – 2016)					
DV:	Distillate Fuel Oil Price	Industrial Natural Gas Price	Industrial Electricity Price	ln(Patent Stock for Green Production)	ln(Patent Stock for Green Transportation)	ln(Patent Stock for Green Infrastructure)
	(1)	(2)	(3)	(4)	(5)	(6)
State-Level Shale Boom	**-0.026****	**-0.979*****	**-0.483***			
	(0.012)	**(0.237)**	**(0.240)**			
Distillate Fuel Oil Price				**0.043**	**0.105**	**-0.183**
				(0.167)	**(0.247)**	**(0.338)**
Industrial Natural Gas Price				**0.036****	**0.020**	**0.003**
				(0.017)	**(0.024)**	**(0.026)**
Industrial Electricity Price				**-0.022**	**-0.013**	**-0.012**
				(0.022)	**(0.030)**	**(0.028)**
ln(Population)	-0.231	5.964	-0.955	-1.072	-2.259	-1.616
	(0.174)	(3.707)	(3.512)	(1.373)	(1.762)	(1.880)
ln(Household Income)	0.032	16.016**	15.988**	-1.423	-2.769***	-3.975**
	(0.187)	(7.208)	(6.377)	(1.383)	(1.004)	(1.850)
Unemployment Rate	-1.283*	5.148	-1.014	1.542	-1.655	-4.459
	(0.687)	(8.473)	(9.288)	(2.877)	(3.708)	(4.296)
ln(Total GDP)	-0.230	-7.461**	-4.312	0.809	1.813**	0.876
	(0.212)	(3.028)	(3.565)	(0.915)	(1.193)	(1.434)
GDP Share of Mining Sector	0.473	6.340	15.101*	-2.579	-2.282	-6.586*
	(0.440)	(5.706)	(8.246)	(1.808)	(2.363)	(3.636)
GDP Share of Utility Sector	-4.087*	109.183	316.157**	-32.560***	13.817	-43.967*
	(2.288)	(134.908)	(134.063)	(11.938)	(35.043)	(24.343)
GDP Share of Manufacturing Sector	0.443	0.288	9.499*	-0.504	1.180	-2.238
	(0.437)	(6.155)	(5.387)	(2.835)	(2.227)	(3.908)
ln(Number of Firms with Patents)	0.001	-0.472**	0.405	0.033	0.045	0.178
	(0.013)	(0.228)	(0.286)	(0.069)	(0.072)	(0.110)
State Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Within R-Squared	0.992	0.670	0.614	0.109	0.302	0.411
Number of Observations	816	816	816	768	768	768

Regression Results

DV: ln(Patent Stock for Green Production)	Industry Sector		Energy Intensity		Energy Mix		
	Goods-Producing Industries	Service-Providing Industries	Higher	Lower	Higher Percentage of Fuel Oil	Higher Percentage of Natural Gas	Higher Percentage of Electricity
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
State-Level Shale Boom	**-0.060*** (0.021)**	**-0.009 (0.017)**	**-0.054** (0.023)**	**-0.024 (0.017)**	**-0.057** (0.022)**	**-0.058*** (0.021)**	**-0.009 (0.018)**
Return on Assets	-0.002** (0.001)	-0.001 (0.001)	-0.002 (0.001)	-0.001 (0.001)	-0.000 (0.001)	-0.001 (0.001)	-0.003* (0.002)
Return on Assets	-0.004 (0.004)	-0.001 (0.002)	-0.004 (0.003)	0.001 (0.002)	-0.004 (0.004)	-0.005 (0.004)	0.000 (0.002)
ln(Sales)	0.029*** (0.010)	0.002 (0.007)	0.026** (0.013)	0.008 (0.006)	0.013* (0.007)	0.015* (0.009)	0.014 (0.011)
ln(R&D Stock)	0.001 (0.010)	-0.004 (0.031)	0.007 (0.021)	-0.001 (0.006	0.003 (0.011)	0.007 (0.011)	0.001 (0.020)
ln(Nongreen Patent Stock)	0.097*** (0.016)	0.048*** (0.017)	0.116*** (0.021)	0.041*** (0.011)	0.075*** (0.015)	0.080*** (0.017)	0.071*** (0.017)
ln(Industry Green Patent Stock)	0.063** (0.027)	0.063 (0.041)	0.053* (0.030)	0.056** (0.028)	0.045*** (0.023)	0.051* (0.027)	0.055 (0.036)
Industry Concentra tion	-0.055 (0.060)	0.046 (0.049)	-0.061 (0.064)	0.022 (0.028)	0.031 (0.040)	-0.092 (0.059)	0.004 (0.056)
Firm Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Within R-Squared	0.080	0.064	0.096	0.041	0.068	0.066	0.063
Number of Observ ations	6,976	5,296	6,112	6,160	6,240	6,208	6,320

- Negative impact is observed for firms that rely on fossil fuel

Regression Results

	State Level Panel Data (2000 – 2016)				
	ln(Industrial Energy Use)	ln(Industrial Electricity Use)	ln(Patent Stock for Green Production)	ln(Patent Stock for Green Transportation)	ln(Patent Stock for Green Infrastructure)
DV:	(1)	(2)	(3)	(4)	(5)
State-Level Shale Boom	**0.212****	**0.065**			
	(0.102)	**(0.039)**			
ln(Industrial Energy Use)			**-0.084****	**-0.030**	**-0.025**
			(0.040)	**(0.052)**	**(0.063)**
ln(Industrial Electricity Use)			**-0.076**	**-0.089**	**-0.348**
			(0.146)	**(0.204)**	**(0.235)**
ln(Population)	2.565*	0.513	-0.360	-1.530	-0.757
	(1.473)	(0.458)	(1.213)	(1.632)	(1.708)
ln(Household Income)	-0.338	-0.851*	-0.625	-2.518***	-4.379***
	(0.931)	(0.442)	(1.083)	(0.764)	(1.058)
Unemployment Rate	-8.133**	-1.499	1.839	-1.028	-3.742
	(3.309)	(1.471)	(2.582)	(3.684)	(4.058)
ln(Total GDP)	1.393	1.189***	0.563	1.746	1.457
	(1.160)	(0.426)	(0.807)	(1.129)	(1.164)
GDP Share of Mining Sector	1.561	0.901	-2.257	-2.145	-6.729*
	(3.088)	(1.203)	(1.743)	(2.370)	(3.644)
GDP Share of Utility Sector	15.813	1.259	-31.629**	12.359	-42.129**
	(19.913)	(9.029)	(11.833)	(31.443)	(20.812)
GDP Share of Manufacturing Sector	-1.636	-0.234	0.395	0.796	-3.335
	(2.044)	(0.864)	(2.611)	(2.066)	(4.152)
ln(Number of Firms with Patents)	-0.025	0.039	0.038	0.052	0.201**
	(0.092)	(0.031)	(0.061)	(0.065)	(0.094)
State Fixed Effects	Yes	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes	Yes
Within R-Squared	0.188	0.220	0.105	0.287	0.405
Number of Observations	867	867	816	816	816

Future Work

- Outcome of interest
  - (Self)-citations measure technological innovation (Jaffe, Trajtenberg, and Henderson 1993; Moretti 2021)
- Industry-specific FE
  - To absorb nationwide time-varying technological and sectoral changes
- Staggered DiD
  - Staggered roll-out of shale boom
  - Late vs. early comparison is forbidden (Goodman-Bacon, 2021)
  - Out of 20 treated states, 17 are treated between 2003 and 2005
  - Not *too much* late vs. early comparison

Conclusion

- Upon the Shale boom, energy-intensive firms that rely more on fossil fuels have a greater incentive to reduce investment in green production
- But, the shale boom has a minimal impact on the areas of innovation that cheaper oil and gas cannot readily substitute
  - Green transportation and infrastructure
- In order to promote green technological innovation under the glut of fossil fuels, policymakers need to reconsider local energy and environmental policies and incentive programs

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