

Does the Shale Gas Revolution Hinder Clean Energy Innovation?

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Abstract

We analyze the causal impact of the U.S. shale gas revolution on technological innovation in the electricity generation sector. Using a country-level data set of electricity patents from 1978-2018, we find that the U.S. shale gas revolution led to a 1.60 decrease in the ratio of green to fossil-fuel electricity patents and a 0.93 decrease in the ratio of renewable to fossil-fuel electricity patents. In addition, we find a 0.15 increase in the share of fossil-fuel electricity patenting. These results suggest that the U.S. shale boom hinder the development of new and improved technologies that ease the decarbonization of the electricity sector.

JEL Classifications: O30, Q43, Q55

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1 Introduction

Technological advancements in horizontal drilling and fracking technologies have resulted in an abundance of low-cost natural gas supplies, leading to changes in the electricity generation sector. For example, between 2005 and 2019, the share of natural gas doubled, displacing coal as the top input in the U.S. electricity generation mix by 2015 (see Figure 1). Although reduced coal use may contribute to a cleaner electricity sector, the shale boom may also affect the use of other inputs, such as renewable sources like sun and wind. Since the share of these renewables is limited due to their variability, their success relies on innovation. To that end, innovation in both renewables and clean technologies remains crucial for the decarbonization of the electricity sector.

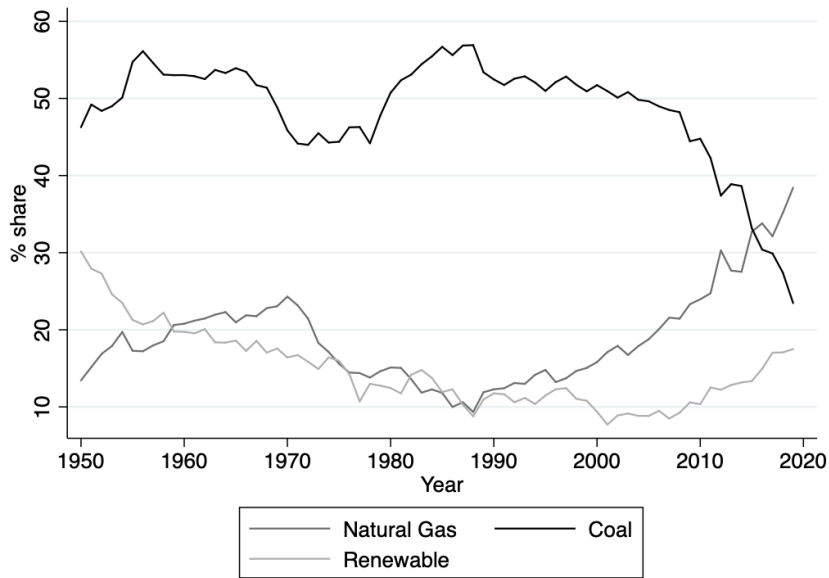


Figure 1: U.S. electricity generation mix, 1950-2020

We investigate the causal impact of the U.S. shale gas revolution on technological change in the electricity generation sector.¹ Specifically, we ask the following question: Does the U.S. shale gas revolution induce a shift away from clean energy innovation in the electricity generation sector? To answer this question, we study innovation activity before and after the U.S. shale boom by tracing the shares of green, renewable, and fossil-fuel patents.² We do so by selecting the Energy Policy

¹Both the shale gas and shale oil include technological advancements; however, we focus on shale gas because it has uniquely transformed electricity generation in the U.S. by displacing coal and driving green innovation (EIA, 2020; Hausman and Kellogg, 2015). In contrast, shale oil has primarily impacted transportation and industry, with limited direct effects on electricity generation (Brown and Yücel, 2013).

²We define green, renewable, and fossil-fuel categories following WIPO’s IPC Green Inventory. We provide a list

Act (EPAAct) of 2005, which relaxes the regulatory constraints on fracking by exempting hydraulic fracturing from the provisions of the Safe Drinking Water Act (SDWA).³ With this, natural gas markets could more easily increase the supply of natural gas (see Figure 2). Furthermore, we take advantage of the fact that only North American countries (United States, Canada, and Mexico) are exposed to fracking development. This provides the opportunity to employ difference-in-differences model using 134 countries and 337,009 patent applications from 1978 to 2018.⁴ With this, we provide the empirical estimate of the causal effect of the U.S. shale gas revolution on innovation in power generation technologies.

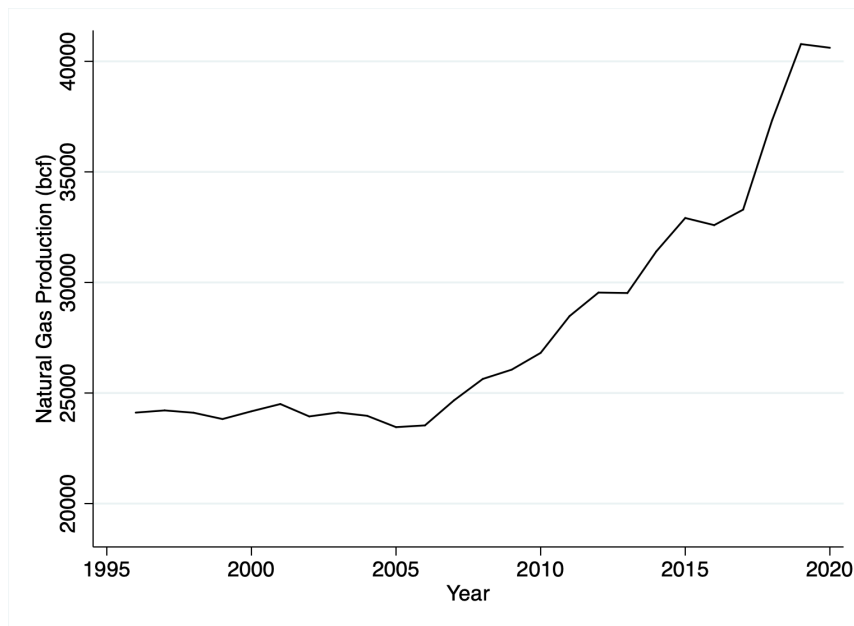


Figure 2: Annual U.S. natural gas production measured as gross withdrawals, 1995-2020

Our empirical results show that the share of patenting in both green and fossil-fuel technologies changes after the U.S. shale gas revolution. Specifically, we find a 0.12 decrease in the ratio of green to total patenting and a 0.15 increase in the ratio of fossil-fuel to total patenting. In addition, our difference-in-differences estimate of the treatment effect implies that the shale boom is responsible for a decrease of 1.60 in the ratio of green to fossil-fuel electricity patents and a decrease of 0.93

of technologies in the Data Section.

³According to the Federal Energy Regulatory Commission (FERC), EPAAct of 2005 is the first major energy law enacted since the New Deal’s Federal Power Act of 1935 and the Natural Gas Act of 1938 (FERC, 2006). Section 322 of the EPAAct of 2005 exempts fracking fluids and underground storage of natural gas from complying with the underground injection well regulations of the Safe Drinking Water Act of 1974 which was established by the U.S. Environmental Protection Agency (EPA) to protect underground drinking water sources (mainly aquifers).

⁴Our baseline results are based on four decades of data, however, we confirm that our results are robust to shorter time spans.

in the ratio of renewable to fossil-fuel electricity patents. These results imply a move away from innovation in green patenting and in favor of fossil-fuel patenting, hindering the development of new and improved technologies that are needed to transition toward a greener electricity sector.

This article contributes to the understanding of innovation in the energy sector.⁵ A large and growing literature on innovation studies the link between energy policy and technological innovation. There is an extensive literature that focuses on how the energy prices re-direct innovation to more energy efficient technology while implicitly considering that more stringent environmental policies increase prices (see for example, Newell et al. (1999); Popp (2002); Lee et al. (2011)).⁶ A second strand focuses on directly testing the environmental policy impact on innovation in addition to the impact of prices and expectations on innovation (see for example, Noailly and Smeets (2015); Sanyal and Ghosh (2013); Calel and Dechezleprêtre (2016); Lazkano and Pham (2016)).⁷

Our work is mostly related to the emerging literature investigating the impact of the shale gas revolution on local economic and environmental outcomes in the U.S..⁸ There are also studies investigating the impacts of shale gas developments on economic outcomes in countries other than the U.S..⁹ These studies have focused on the microeconomic outcomes of the U.S. shale gas revolution, while our focus is on innovation. Thus, our work is closely related to Acemoglu et al. (2019) who motivate their paper by first documenting a decline in green innovation since the shale gas boom. Popp et al. (2020) also document a decline in clean energy patenting since 2010 but focus instead on the changing nature of innovation in the energy sector.

Our analysis focuses on documenting the change in the shares of green, renewable, and fossil-fuel technological innovations, in addition to conducting a synthetic control analysis. While other studies focus on the mechanisms that drive innovation, we focus on documenting the change in the shares of green, renewable, and fossil-fuel technological innovations caused by the shale gas boom at the country level. By doing so, we provide empirical evidence that the shale boom hinders

⁵Popp et al. (2019) offers an excellent and extensive review of the developments in this literature.

⁶In addition to prices and policies, Martin et al. (2011) find a significant and positive association between firms' expectations about future stringency and clean innovation, implying that innovation may also be driven by expectations following a policy change.

⁷Noailly and Smeets (2015) ask whether policy shifts innovation away from fossil fuels toward renewable energy and find that innovation comes from new entrants to the market, while Lazkano and Pham (2016) evaluates the role of a fossil fuel tax and research subsidy in directing innovation from fossil fuel toward renewable energy technologies in the electricity sector. However, innovation in response to policy also occurs at upstream equipment manufacturers (Sanyal and Ghosh, 2013), and regulated and unregulated firms (Calel and Dechezleprêtre, 2016).

⁸For example, Wu and Jiang (2022); Han (2020) focus on local innovation, Muehlenbachs et al. (2015) focus on housing prices, Hausman and Kellogg (2015); Feyrer et al. (2017); Bartik et al. (2019) focus on local and sectoral welfare, Holladay and LaRiviere (2017) focus on emissions, some others focus on the impact of shale gas on greenhouse gas emissions in the medium term (Kersting et al., 2018) and in the long term (Acemoglu et al., 2019) in the electricity generation sector.

⁹In China, for example, shale gas drilling is still in its developmental stage. The country's first shale gas exploration production-sharing contract had been signed around early-2012, the first tranche of pilot shale gas wells had been dug, and commercial production was yet to begin as of mid-2012 (Gunningham, 2014). Furthermore, Mei et al. (2022) considers three indicators of regional economic development (regional GDP, employment level, and the housing price index) using data from China's largest shale gas region.

green innovation while boosting fossil-fuel innovation, which may have negative implications for the decarbonization of the electricity sector.

The paper proceeds as follows. In section 2, we summarize the facts and events that sparked the U.S. shale gas revolution. Section 3 presents the empirical model while Section 4 discusses our empirical results. Section 5 concludes.

2 Timing of the U.S. shale gas revolution

In the following we briefly describe natural gas markets and the importance of the EPAct of 2005 for the U.S. power sector.¹⁰ The ongoing U.S. shale gas revolution has increased energy production and accelerated the retirement of coal power plants, all of which were made possible by technological breakthroughs resulting from cooperation between the natural gas industry and the federal government since the late 1990s (Wang et al., 2014). While primary shale gas research began in the U.S. in the mid-1970s due to public-private partnerships, the development and testing of fracking technology to extract shale gas lasted until the early 2000s (Soeder, 2012).

Fracking activities pose risks of contamination of underground and surface waters, therefore, drilling activities were subject to EPA regulations. While the adoption of fracking technology was gradually enabled by innovations in horizontal drilling and hydraulic fracturing (Wang and Krupnick, 2015), some have argued that regulatory changes – particularly the exemption of fracking from the EPA’s Safe Water Drinking Act (SWDA) regulations, may have removed key barriers to its widespread commercial deployment since the stringent water regulations have historically encouraged firms and investors to pursue cleaner production technologies (Gray and Shadbegian, 1998). Following this policy change, domestic natural gas production began to rise substantially (see Figure 2). While we do not claim the EPAct of 2005 solely caused the shale gas boom, we use it as a policy marker to study how the expansion of shale gas production affects innovation outcomes.

Natural gas has become a vital energy resource because of the rapid increase in shale gas supply. The global natural gas market is segmented into three distinct regions: North America, Europe, and Asia. Unlike North America, where advanced extraction technologies have driven significant production, comparable technologies are not yet available in Europe or Asia. This has led to notable differences in natural gas price trends across these regions (Paltsev and Zhang, 2015; Geng et al., 2016). Consequently, in contrast to the more unified global oil market regional natural gas markets remain unintegrated.

We select the EPAct of 2005 policy to study the impact of the shale gas boom in innovation

¹⁰We explore the timing of the U.S. shale gas boom before and after 2005. On the one hand, we explore a later timing because it may take several years for changes in research to translate into patent applications. On the other hand, we explore the endogeneity of this timing because it is possible that the shale gas revolution was a result of previous technological advancements. We consider both an earlier and a later timing in our robustness analysis.

activity. There may be a potential endogeneity between EAct of 2005 and innovation activity, which would bias our empirical results. To explore this possibility, we carry out an event study and present our results in Figures A1 in the appendix. The event study coefficients fluctuate around zero and are not significantly different from zero the years before 2005, showing no evidence for a pre-treatment trend. In addition, study pre-treatment trends, and whether they could be driving the difference in innovation activity (see Figure A2). We test the parallel trend assumption by taking into account year-to-year variability; we do so because there are more than two pre-treatment years. As seen in Table A2, the parallel trend test coefficients are fluctuating around zero and are not significantly different than zero for years before 2005, providing evidence for parallel trends. Based these results, we make an exogeneity assumption of the Act and we carry on with our difference-in-differences analysis.

3 Data

We measure technological innovation with the number of patent applications.¹¹ We drew data from the OECD REGPAT database and utilize International Patent Classification (IPC) codes to distinguish fossil-fuel, green, and renewable electricity generation technologies. Specifically, we use the list of IPC codes from Lanzi et al. (2011) to select fossil-fuel electric patents whereas we select IPC codes of green and renewable electricity patents based on WIPO’s IPC Green Inventory. Fossil fuel electricity generation technologies include coal gasification, fluid bed combustion, boilers for steam generation, steam engines, superheaters, gas turbines, combined cycle generators, compression ignition engines, and co-generation. In contrast, green power technologies include biofuels, fuel cells, energy recovery from manmade waste, and renewable sources such as hydro, wind, solar, geothermal energy, and other production or use of heat not derived from combustion, such as using natural heat and waste heat. Notably, renewable energy is a subset of green energy, specifically including geothermal, hydro, wind, and solar technologies.

In total, we identify 337,009 patent applications filed in electricity generation technologies related to fossil-fuel, green, and renewable resources across 134 countries between 1978 and 2018.¹² ¹³ Figure 3 shows the evolution of patent applications in the U.S. in green and renewable technologies.

¹¹We focus on the quantity of patents rather than their quality. However, in our robustness analysis, we account for patent quality by using citation-weighted patent counts. The estimation results based on citation-weighted patent counts remain consistent with the baseline findings in terms of sign and significance across all samples and technologies, though the magnitudes are larger.

¹²See the list of countries in Table A1. We overlook technology transfers between countries because, with the exception of some energy efficiency technologies, clean technologies do not often move across borders unless the destination country’s environmental regulations give incentives to embrace them (Haščič and Johnstone, 2011; Popp, 2020).

¹³Patent data are available from 1963 to 2021. Out of these years, we restrict our estimation sample to 1978-2018. We use patent data for the first 15 years, 1963-1978, to construct pre-sample variables. Furthermore, we drop the last three years of data to address truncation in the dataset.

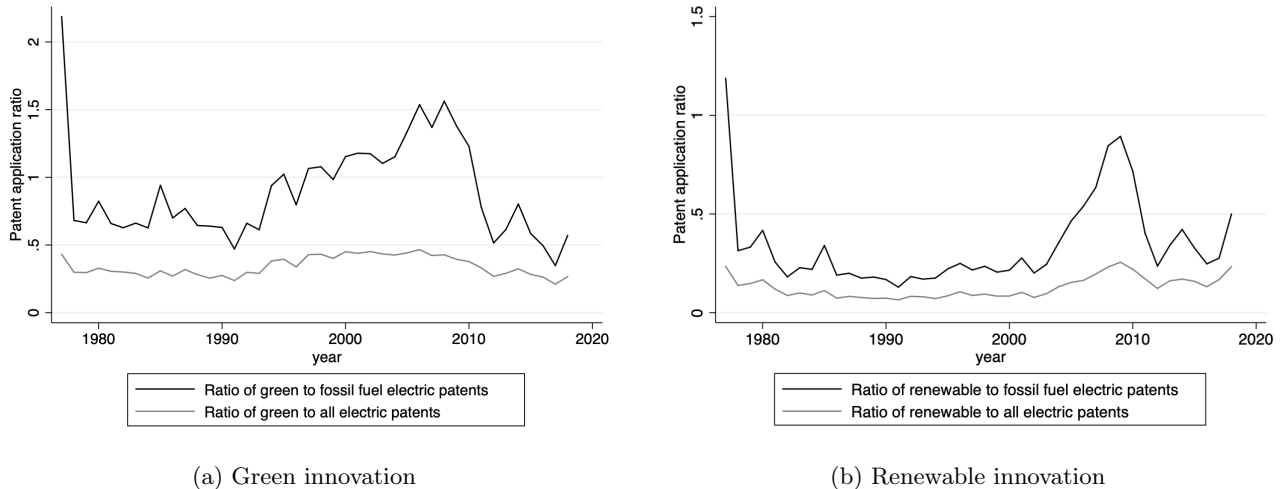


Figure 3: Annual aggregate patent count in the U.S., 1976-2018

In addition to the patent applications data, we rely on energy price data from Energy Information Agency (EIA), and other commonly known determinants of innovation such as GDP, electricity production, and labor statistics from the Penn World Tables.

4 Empirical model

We evaluate the causal impact of the U.S. shale gas revolution on innovation activity by estimating a difference-in-difference (DiD) model with fixed effects. Our baseline specification is:

$$Y_{it} = \beta_0 + \beta_1 \times D_t^{\text{Post}} \times D_i^{\text{Treat}} + \beta_2 \times D_t^{\text{Post}} + \delta_i + \phi_t + \alpha \times X_{it} + \epsilon_{it}, \quad (1)$$

where Y_{it} is our measure of innovation in country i in year t .¹⁴ Specifically, we consider the following five patent ratios: 1) green to fossil-fuel patents, 2) green to total patents, 3) renewable to fossil fuel patents, 4) renewable to total patents, and 5) fossil fuel patents to total patents.¹⁵ D_t^{Post} is a year dummy equal to one after 2005 whereas D_i^{Treat} is a treatment dummy equal to one for countries exposed to the shale gas revolution (United States, Canada, and Mexico).¹⁶ δ_i is the

¹⁴While firm-level innovation incentives occur, economy-wide studies of innovation, such as those using country-level patent data, will capture innovations from all firms, whereas firm-level studies may not. Therefore, this study focus on country-level patent data.

¹⁵Since the patentability of innovations varies across technologies, we focus on relative indicators (e.g. the share of green patents in the fossil-fuel patents in that country) rather than comparing absolute figures (e.g. the count of patents in a given country) (Glachant and Dechezleprêtre, 2017).

¹⁶In the full sample, 3 out of 134 countries are treated. In the EU sub-sample, 3 out of 27 countries are treated, and in the Top Green sub-sample, 3 out of 10 countries are treated.

country fixed effect that accounts for unobserved and time-invariant country heterogeneity, while ϕ_t is the time trend that accounts for a common trend. The interaction term captures the unobserved heterogeneity over time such as impact of environmental policies over time. X_{it} is vector of control variables including real GDP, spark spread, and the prices of natural gas and electricity.¹⁷¹⁸ Finally, ϵ_{it} is the error term. We cluster the standard errors at the country level.

The coefficient of interest is β_1 , which captures the causal effect of the shale gas revolution on innovation activity. For instance, when the dependent variable is the ratio of green to fossil-fuel patents, a negative β_1 tells us that the shale gas boom leads to a fall in the ratio of green to fossil-fuel patents, suggesting a move away from green innovation in the electricity generation sector. In our baseline estimations, the control group includes 131 countries. In addition, we consider two other control groups as a sensitivity analysis: (1) countries in Europe and (2) highly innovative countries with at least a 10% share of natural gas in electricity generation.¹⁹

5 Estimation Results

This section presents our main findings of the impact of the shale gas boom on innovation in the electricity sector. Table 1 shows the results of the DiD regression model in equation 1, where we control for country fixed effects and a time trend.²⁰ In the first three columns, the control group includes 131 countries, while columns four to six include European countries and the last three columns includes highly innovative countries. In Table A4, we measure innovation with the total number of patent applications in each technology group.

We first discuss the results on green innovation. We find a statistically significant and negative impact on green innovation. Specifically, the shale gas revolution leads to a 1.60 decrease in the ratio of green to fossil-fuel patents in North American countries when comparing it to the baseline sample (Table 1, Panel A, column 1). In addition, green innovation relative to fossil fuels reduces by 1.19 and 1.69 when comparing it to European countries and top innovators, respectively (Table 1, Panel A, columns 4 and 7). We further study green innovation in Panel B where the measure of innovation is the ratio of green to total innovation. We also find a statistically significant and negative impact; however, the magnitude of the impact is smaller than before. Specifically, the shale gas revolution decreases green to total innovation by 0.12 in our baseline sample, by 0.12

¹⁷The spark spread is the difference between the wholesale market price of electricity and its cost of production using natural gas.

¹⁸Since both GDP and energy prices are related to our treatment, we consider an alternative specification that excludes these variables.

¹⁹When we consider alternative control groups, the number of countries is smaller and therefore we bootstrap standard errors.

²⁰We control for country and year fixed effects in Table A3. There are insufficient observations to compute bootstrap standard errors with the EU and Top Green sub-samples (columns 4-9). Thus, Table A3 present our estimation results with year fixed effects and without bootstrapped standards errors. These estimation results are in line with our baseline estimations.

in the European sample, and 0.17 in the top green country sample (Panel B, columns 1, 4, 7). These results confirm that the shale boom contributed to less green innovation, which possesses an additional challenge to decarbonize the electricity sector.

Next, we focus on renewable technologies. As before, we find a statistically significant and negative impact on the share of renewable to fossil-fuel innovation, however, we find an insignificant impact on the share of renewable to total innovation. Specifically, the ratio of renewable to fossil-fuel electricity patenting decreases by 1.19 compared to our baseline sample (Table 1, Panel C, column 1). Furthermore, we find that renewable innovation relative to fossil-fuel innovation of North American countries falls by 0.70 and 0.42 compared to European countries and top innovator countries, respectively (Table 1, Panel C, columns 4 and 7). These results are more optimistic for renewable technologies as a total share of innovation in the electricity sector.

Finally, Panel E presents innovation in fossil-fuel technologies. Overall, we find a significant and positive impact on the fossil-fuel to total electricity patenting. Specifically, the ratio increases by approximately 0.15 when comparing the North American countries to baseline and counterfactual samples (Table 1, Panel E, columns 1, 4, 7). These results imply that the shale gas revolution contributed to a further boost in patenting in fossil-fuel technologies.

To complete our empirical analysis, we discuss potential caveats associated with our analysis and carry out several robustness checks of our results. In the first analysis, we measure innovation in equation 1 with the total number of patent applications in each technology group, and present the DiD results in Table A4. Our goal with this analysis is to understand the changes in patenting activity in treated groups compared to what we expect would have happened if the shale gas revolution never happened.²¹ These results are presented in Table A4, which shows that the shale gas revolution has a statistically insignificant effect on the number of patent applications. The signs of the point estimates show a rise in fossil-fuel electricity patenting (Table A4, Panel C, column 1) and renewable electricity patenting (Table A4, Panel B, column 1) and a fall in patenting in green electricity (Table A4, Panel A, columns 1) and total electricity patenting (Table A4, Panel D, columns 1). Note, however, that unlike our baseline estimations, these estimates are statistically insignificant.

Second, we consider an alternative timing of the shale gas boom in our analysis. Since it takes several years for changes in research to translate into patent applications, we consider 2007 as the timing of the shale gas boom. These results are consistent with our main results. In addition, to explore the possibility that the shale gas revolution is the result of prior innovations related to fracking safety, we run a placebo test. Specifically, we consider an alternative start year of the treatment period. The US pioneered the commercial use of fracking technologies in the late 1990s

²¹The point estimates in Table A4 may overestimate the impact of the shale gas revolution of 2005 because unobservable characteristics could drive patent applications in different technology groups and the point estimates only take observable characteristics into account. For this reason, and following Popp (2002), we use patent ratios in Table 1.

Table 1: Treatment effects for green, renewable-energy and fossil-fuel technology innovation *ratios*, from 1978 to 2018.

	World			Europe			Top Green		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A: GREEN/FF									
DiD Coefficient	-1.60***	-1.64***	-1.34**	-1.27***	-1.33***	-1.59***	-1.69***	-1.70***	-1.46***
se	0.40	0.41	0.52	0.38	0.37	0.45	0.64	0.64	0.56
Panel B: GREEN/Total									
DiD Coefficient	-0.12***	-0.12***	-0.12***	-0.12***	-0.12***	-0.13***	-0.15***	-0.15***	-0.12***
se	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.03
Panel C: REN/FF									
DiD Coefficient	-0.93***	-0.96***	-0.90**	-0.76***	-0.81***	-1.07***	-0.84**	-0.85**	-0.98**
se	0.30	0.31	0.43	0.29	0.27	0.38	0.19	0.18	0.23
Panel D: REN/Total									
DiD Coefficient	-0.02	-0.02	-0.2	-0.02	-0.02	-0.35	-0.04	-0.04	-0.03
se	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03
Panel E: FF/Total									
DiD Coefficient	0.15***	0.15***	0.14***	0.14**	0.15**	0.16**	0.18***	0.18***	0.13**
se	0.04	0.04	0.04	0.07	0.07	0.06	0.06	0.06	0.06
Country FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Time trend	YES	YES	YES	YES	YES	YES	YES	YES	YES
Interaction	YES	YES	YES	YES	YES	YES	YES	YES	YES
Real GDP	YES	YES	YES	YES	YES	YES	YES	YES	YES
Spark Spread	YES	NO	NO	YES	NO	NO	YES	NO	NO
Price:Electr	NO	YES	NO	NO	YES	NO	NO	YES	NO
Price:NATGAS	NO	NO	YES	NO	NO	YES	NO	NO	YES

Significance levels: * : 1% : 5% : 10%.

Standard errors of the baseline sample are clustered at the country level.

For the counterfactual groups, we are using bootstrap estimate using 100 replications.

and early 2000s, driven by innovation in horizontal drilling and hydraulic fracturing techniques. We consider a start date of 1998 to indicate a year when fracking was available and before the 2005 regulatory change. The estimation results show that none of the DiD coefficients were statistically significant, thus, our placebo analysis shows that the availability of technology was not statistically significant at promoting the shale gas revolution.²²

In addition to the two sub-samples analyzed in our baseline Table 1, we consider alternative sub-samples to address potential concerns about the composition of the control group. First, we exclude EU countries from our analysis to examine whether the implementation of the EU ETS market influenced innovation. Although this exclusion reduces the size of the control group and may diminish the statistical power of the analysis, it tests whether the baseline results are sensitive to the presence of EU countries. The results confirm that our findings are not driven by the combined effects of the EU ETS and the US shale gas revolution but are instead attributable to

²²In addition, we applied the Weibull hazard model to test for potential reverse causality. None of the coefficients on the lagged dependent variables were found to be statistically significant, indicating that past values of the outcome variable do not influence the timing of the treatment. This result suggests that there is no evidence of reverse causality affecting our findings.

the policy change analyzed in Table 1. Next, we exclude countries with significant state ownership in the energy sector. The estimation results remain consistent across these additional sub-samples, with the same signs and levels of statistical significance as in the baseline model, confirming the robustness of our findings.

Next, we employ synthetic control (SCM) method because it allows us to analyze each treatment country separately in addition to addressing the issue of unbalanced sample size between treatment and control groups. Figure A3 shows that the U.S. shale gas revolution decreases the ratio of green to fossil-fuel patents, green to total patents, renewable to fossil-fuel patents, and renewable to total patents, while increasing the share of fossil-fuel innovation in the U.S.

Finally, we address several concerns related to our specification. First, one may argue that the EAct is one part of a group of policies implemented in the energy sector and that our point estimates may capture the impact of other energy policies. To address this, we consider an alternative specification of equation 1 that includes an interaction term between country-fixed effects and post-treatment dummy.²³ The results in Table A5 are consistent with our baseline estimates, which validate our main conclusions. A second concern relates to the choice of control variables. Specifically, we remove GDP and energy prices because they can be affected by the treatment. The estimation results excluding the control variables in Table A6 show that our main results are robust to this specification change. Specifically, we find that using the World and EU samples, the estimated coefficients maintain the statistical significance and signs as in the baseline estimations. The sample focusing on top green innovators, the estimation coefficients maintain the same sign in all our measures of innovation. The statistical significance of these measures of innovation holds in panels A, B and E, but not for panels C and D. Overall, these alternative specifications show that our main results presented in Table 1 are robust.

6 Conclusion

Technological innovations offer a roadmap for reducing clean energy costs and increasing conventional fossil-fuel efficiency. For example, advancements in shale gas extraction techniques significantly contributed to driving some coal-fired power plants out of the power sector. In addition to aiding the phase-out of coal, the abundance of low-cost natural gas has implications for the invention and development of green and renewable technologies.

We study innovation before and after the U.S. shale gas revolution by tracing the shares of green, renewable, and fossil-fuel patenting in the electricity generation sector using a difference-in-difference model. Our approach leverages an exogenous shift in fracking activity in the U.S. natural gas sector following the EAct of 2005, which eased regulatory barriers to facilitate broader fracking

²³This interaction term helps capture country-specific effects in response to the treatment over time, which allows each country respond differently to the EAct of 2005 due to differences in policy environments.

adoption. Whereas past economic research on the impacts of the shale gas revolution focuses on the local microeconomic outcomes, our analysis aims to shed light on possible aggregate influences on innovation activity. Our findings suggest that the policy change may have encouraged patenting in fossil-fuel-related electricity generation technologies relative to green-focused innovations, with little observable effect on renewable technology development. Although indicative of a shift away from green innovation, these results should be interpreted with caution, as the longer-term impact on decarbonization goals remains complex.

Future research could further explore the distinct impacts of the shale gas revolution on natural gas technologies relative to other fossil fuel and renewable innovations. Since the shale gas revolution primarily affects natural gas markets, examining its influence on natural gas versus other fossil fuel-based technologies may yield valuable insights. Additionally, because various renewable sources may respond differently to shifts in energy markets and policy incentives, analyzing these differences could help identify specific drivers of innovation across renewable technologies. Investigating both short-term and long-term effects would also provide a more nuanced understanding of the shale gas revolution's immediate and lasting influence on electricity generation, offering a comprehensive view of its role in shaping clean energy transitions.

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Appendices

A Data analysis

Table A1: Countries included in baseline and comparison groups

Sample Name	Countries
World	Albania, Algeria, Andorra, Angola, Argentina, Armenia, Aruba, Australia, Austria, Bahamas, Bahrain, Barbados, Belarus, Belgium, Belize, Bermuda, Bhutan, Bolivia, Bosnia and Herzegovina, Brazil, British Virgin Islands, Brunei Darussalam, Bulgaria, Canada, Cayman Islands, Chad, Chile, China, Colombia, Cook Islands, Croatia, Curaçao, Cyprus, Czechia, Denmark, Dominica, Dominican Republic, East Germany, Ecuador, Egypt, El Salvador, Estonia, Faroe Islands, Finland, France, Georgia, Germany, Gibraltar, Greece, Guatemala, Hong Kong, Hungary, Iceland, India, Indonesia, Iran, Ireland, Israel, Italy, Jamaica, Japan, Jersey, Jordan, Kazakhstan, Kenya, Kuwait, Kyrgyzstan, Latvia, Lebanon, Liberia, Liechtenstein, Lithuania, Luxembourg, Macao, Malta, Mauritius, Mexico, Moldova, Monaco, Morocco, Namibia, Netherlands, New Zealand, North Korea, Norway, Oman, Pakistan, Panama, Paraguay, Peru, Philippines, Poland, Portugal, Qatar, Romania, Russia, Saudi Arabia, Serbia, Seychelles, Singapore, Slovakia, Slovenia, Solomon Islands, Somalia, South Africa, South Korea, Soviet Union, Spain, Sri Lanka, Sudan, Suriname, Sweden, Switzerland, Syria, Taiwan, Tajikistan, Tanzania, Thailand, Trinidad and Tobago, Tunisia, Turkey, Turkmenistan, Turks and Caicos Islands, Uganda, Ukraine, United Arab Emirates, United Kingdom, United States, Uruguay, Uzbekistan, Venezuela, Vietnam, Western Sahara, Yemen, Zambia, Zimbabwe.
Europe	Austria, Bosnia and Herzegovina, Bulgaria, Cyprus, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, Greece, Croatia, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Poland, Portugal, Romania, Sweden, Slovenia, Slovakia.
Top Green	Canada, Denmark, France, Germany, Great Britain, Italy, Japan, Korea, Netherlands, United States.

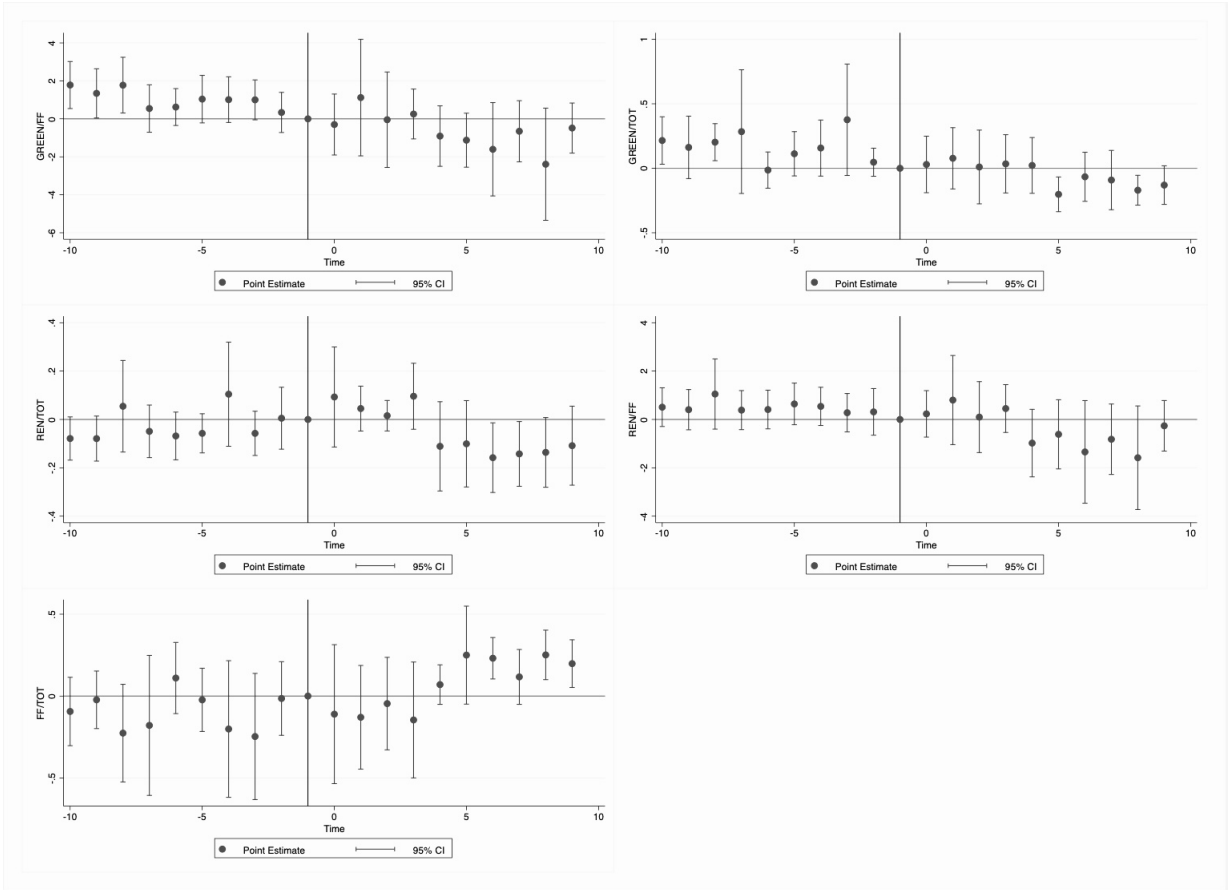


Figure A1: Event study using the world sample.

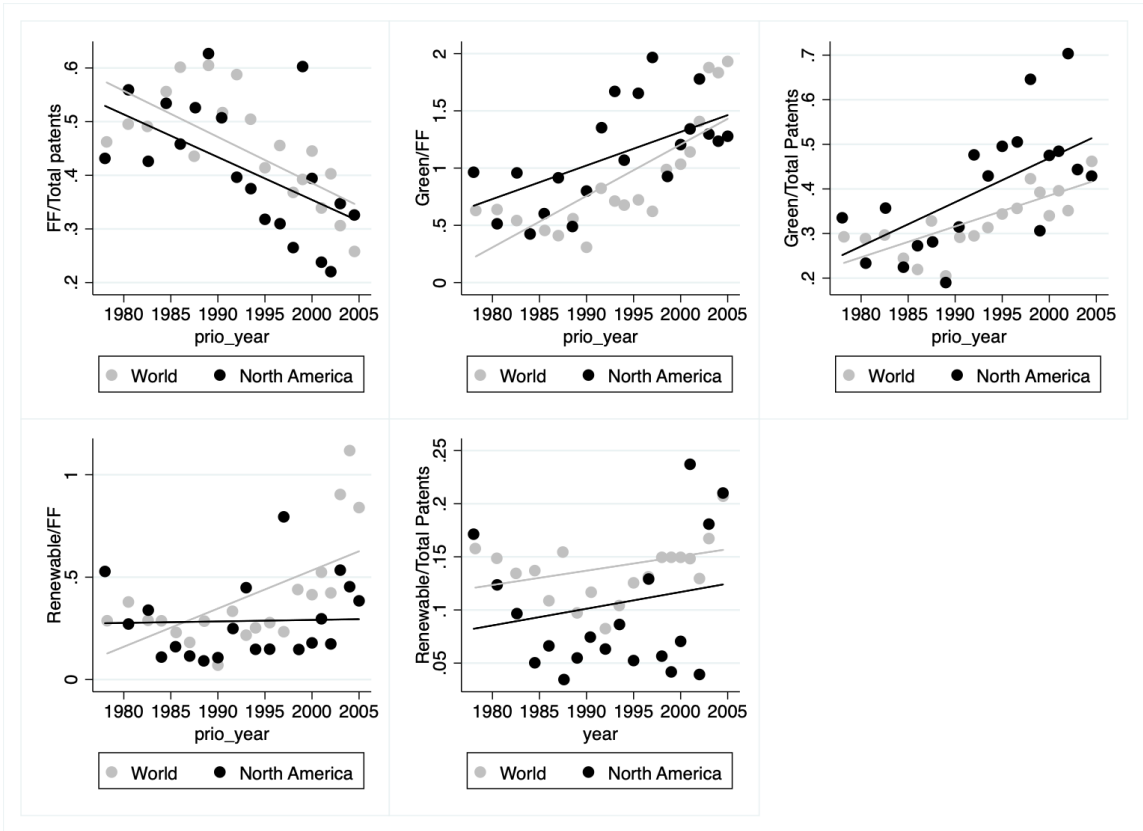


Figure A2: Pre-trends of innovation activity, World.

Table A2: Testing parallel trends test for the pre-treatment period.

	World			Europe			Top Green		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A: GREEN/FF									
$D^{Treat} \times Year_t$	-0.004	-0.01	-0.004	0.005	-0.001	0.005	-0.02	-0.04*	-0.02
se	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Panel B: GREEN/Total									
$D^{Treat} \times Year_t$	0.004	0.003	0.004	0.004	0.003	0.004	0.0003	-0.0004	0.0003
se	0.002	0.003	0.002	0.003	0.003	0.003	0.002	0.002	0.002
Panel C: REN/FF									
$D^{Treat} \times Year_t$	-0.01	-0.01	-0.01	-0.01	-0.02*	-0.01	-0.009	-0.001	-0.009
se	0.01	0.01	0.01	0.01	0.01	0.01	0.008	0.008	0.008
Panel D: REN/Total									
$D^{Treat} \times Year_t$	0.001	-0.0002	0.001	0.0007	-0.0008	0.0006	0	-0.001	0
se	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.001	0.001
Panel E: FF/Total									
$D^{Treat} \times Year_t$	-0.001	-0.0001	-0.001	-0.001	-0.0003	-0.001	0.001	0.003	0.001
se	0.004	0.004	0.004	0.004	0.004	0.004	0.003	0.003	0.003
Country FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Time trend	YES	YES	YES	YES	YES	YES	YES	YES	YES
Interaction	YES	YES	YES	YES	YES	YES	YES	YES	YES
Spark Spread	YES	NO	NO	YES	NO	NO	YES	NO	NO
Price:NATGAS	NO	YES	NO	NO	YES	NO	NO	YES	NO
Price:Electr	NO	NO	YES	NO	NO	YES	NO	NO	YES

Significance levels: : 1% : 5% : 10%.

Notes: We employ an equivalence test to test whether the allowing some variability in pre-treatment period since there are more than two pre-treatment years. We test the difference between the pre-treatment slopes of treated and control group. Specifically, we regress: $Y = \beta_0 + \beta_1 \times Year_t + \beta_2 \times D^{Treat} + \beta_3 Year_t \times D^{Treat} + \delta_c + \phi_t + \alpha \times [covariates] + \epsilon$. Y is our measure of innovation, specifically, the following five patent ratios: 1) green to fossil-fuel patents, 2) renewable to total patents, 3) renewable to fossil fuel patents, 4) renewable to total patents, and 5) fossil fuel patents to total patents. D^{Treat} is a treatment dummy equal to one for countries exposed to the shale gas revolution (United States, Canada, and Mexico) whereas $Year_t$ is continuous year variable. δ_c is the country fixed effect, while ϕ_t is the time fixed. The *covariates* include real GDP, spark spread, and the prices of natural gas and electricity. Finally, ϵ is the error term. If $\beta_3 = 0$, then treatment and control groups have the same slope, that is $E[Y]$ has been changing the same rate.

Table A3: Treatment effects for green, renewable-energy, and fossil-fuel technology innovation ratios using year fixed effects.

	World			Europe			Top Green		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A: GREEN/FF									
Diff-in-diff	-1.631***	-1.675***	-1.425**	-1.309***	-1.382***	-1.739***	-1.695***	-1.713***	-1.665***
se	(0.417)	(0.433)	(0.576)	(0.483)	(0.483)	(0.490)	(0.541)	(0.540)	(0.568)
Panel B: GREEN/Total									
Diff-in-diff	-0.122***	-0.124***	-0.125***	-0.123***	-0.126***	-0.143***	-0.148***	-0.148***	-0.123***
se	(0.0332)	(0.0327)	(0.0329)	(0.0456)	(0.0457)	(0.0465)	(0.0304)	(0.0304)	(0.0314)
Panel C: REN/FF									
Diff-in-diff	-0.954***	-0.986***	-0.980*	-0.794**	-0.854**	-1.203***	-0.849**	-0.863**	-1.132***
se	(0.316)	(0.321)	(0.483)	(0.398)	(0.399)	(0.403)	(0.422)	(0.421)	(0.437)
Panel D: REN/Total									
Diff-in-diff	-0.0229	-0.0242	-0.0375	-0.0230	-0.0249	-0.0483	-0.0340	-0.0345	-0.0393*
se	(0.0460)	(0.0455)	(0.0413)	(0.0331)	(0.0332)	(0.0339)	(0.0212)	(0.0212)	(0.0221)
Panel E: FF/Total									
Diff-in-diff	0.150***	0.153***	0.161***	0.149**	0.154**	0.180***	0.174***	0.174***	0.144***
se	(0.0492)	(0.0478)	(0.0483)	(0.0631)	(0.0632)	(0.0643)	(0.0430)	(0.0430)	(0.0448)
Country FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Interaction	YES	YES	YES	YES	YES	YES	YES	YES	YES
Real GDP	YES	YES	YES	YES	YES	YES	YES	YES	YES
Spark Spread	YES	NO	NO	YES	NO	NO	YES	NO	NO
Price:Electr	NO	YES	NO	NO	YES	NO	NO	YES	NO
Price:NATGAS	NO	NO	YES	NO	NO	YES	NO	NO	YES

Significance levels: * : 1% : 5% : 10%.

Standard errors clustered at the country level.

Table A4: Treatment effects for green, renewable-energy and fossil-fuel patent *applications*, from 1978 to 2018.

	World		Europe				Top Green		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A: Green electric patents									
DiD Coefficient	-70.06	-70.37	-90.10	-64.09	-61.76	-58.75	-324.5	-320.76	-331.75
se	62.31	62.65	74.95	58.37	57.38	63.10	211.11	211.92	205.51
Panel B: Renewable electric patents									
DiD Coefficient	45.66	45.85	33.83	41.26	42.63	33.65	-46.69	-45.73	-54.20
se	87.55	87.62	87.33	88.91	88.94	90.03	91.86	91.92	87.91
Panel C: Fossil-fuel electric patents									
DiD Coefficient	9.65	11.40	-1.49	-6.86	-2.34	-2.55	-57.07	-55.72	-71.37
se	52.54	52.95	45.20	46.46	46.83	43.18	52.95	55.01	43.09
Panel D: Total electric patents									
DiD Coefficient	-37.62	-35.92	-81.88	-53.06	-44.67	-46.86	-450.70	-444.25	-483.52
se	183.87	184.56	182.28	176.06	176.31	187.97	352.35	355.73	323.59
Country FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Time FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Interaction	YES	YES	YES	YES	YES	YES	YES	YES	YES
Real GDP	YES	YES	YES	YES	YES	YES	YES	YES	YES
Spark Spread	YES	NO	NO	YES	NO	NO	YES	NO	NO
Price:Electr	NO	YES	NO	NO	YES	NO	NO	YES	NO
Price:NATGAS	NO	NO	YES	NO	NO	YES	NO	NO	YES
Observations	904	904	904	619	619	619	273	273	273
Adjusted R^2	0.13	0.13	0.13	0.17	0.17	0.18	0.35	0.36	0.34

Significance levels: : 1% : 5% : 10%.

Standard errors are clustered at the country level.

For the counterfactual groups, we are using bootstrap estimate using 100 replications.

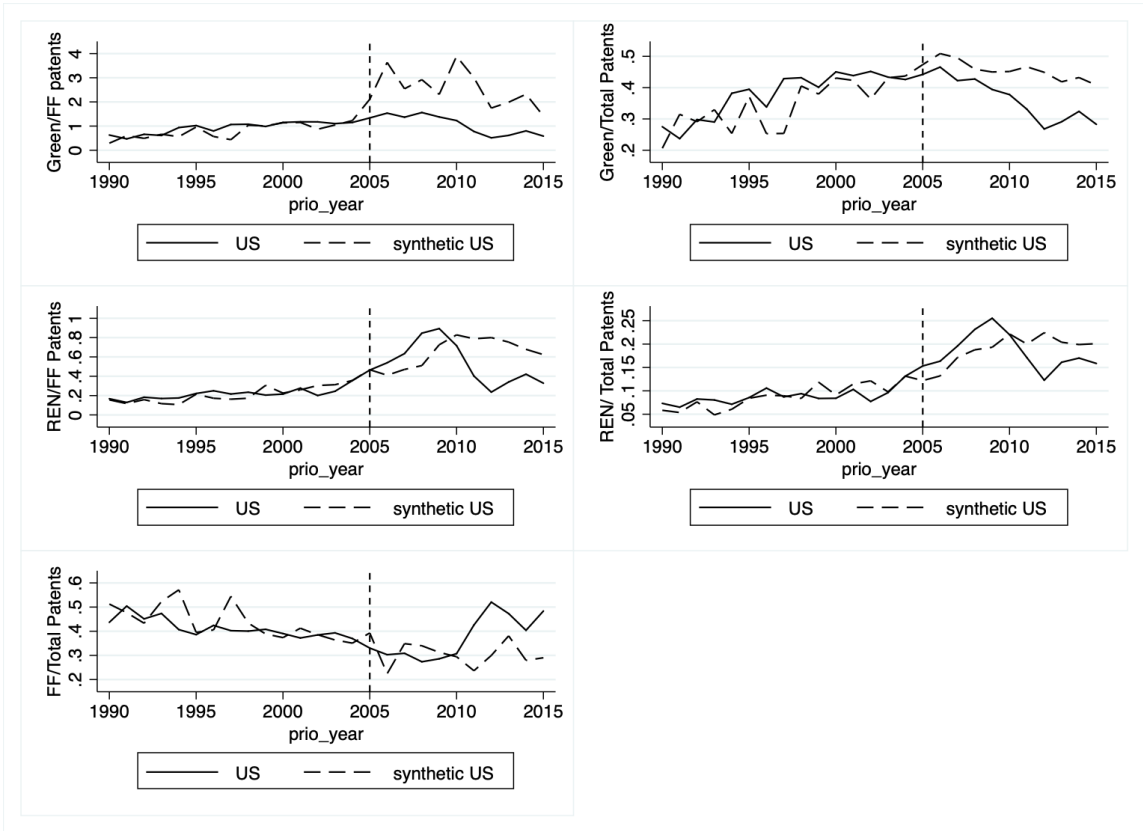


Figure A3: Synthetic control estimation on innovation activity in the electricity sector.

Table A5: Treatment effects for green, renewable-energy and fossil-fuel technology innovation ratios *controlling for other energy policies*, from 1978 to 2018.

	(1)	World (2)	(3)	(4)	Europe (5)	(6)	(7)	Top Green (8)	(9)
Panel A: GREEN/FF									
DiD Coefficient	-1.57***	-1.60***	-1.31**	-1.36***	-1.43***	-1.13***	-1.89***	-1.70***	-1.46***
se	0.40	0.41	0.51	0.33	0.39	0.42	0.42	0.38	0.38
Panel B: GREEN/Total									
DiD Coefficient	-0.12***	-0.12***	-0.12***	-0.12***	-0.12***	-0.13***	-0.20***	-0.20***	-0.19***
se	0.03	0.03	0.02	0.03	0.03	0.03	0.04	0.04	0.05
Panel C: REN/FF									
DiD Coefficient	-0.88***	-0.91***	-0.90**	-0.62**	-0.67**	-0.89***	-0.39**	-0.39**	-0.38*
se	0.30	0.30	0.43	0.26	0.27	0.33	0.19	0.17	0.20
Panel D: REN/Total									
DiD Coefficient	-0.01	-0.01	-0.02	-0.02	-0.02	-0.03	0.01	0.01	0.01
se	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.02
Panel E: FF/Total									
DiD Coefficient	0.14***	0.14***	0.14***	0.14**	0.14**	0.15**	0.17***	0.17***	0.16***
se	0.04	0.04	0.04	0.06	0.06	0.06	0.05	0.05	0.05
Country FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Time trend	YES	YES	YES	YES	YES	YES	YES	YES	YES
Interaction	YES	YES	YES	YES	YES	YES	YES	YES	YES
Expectations	YES	YES	YES	YES	YES	YES	YES	YES	YES
Real GDP	YES	YES	YES	YES	YES	YES	YES	YES	YES
Spark Spread	YES	NO	NO	YES	NO	NO	YES	NO	NO
Price:Electr	NO	YES	NO	NO	YES	NO	NO	YES	NO
Price:NATGAS	NO	NO	YES	NO	NO	YES	NO	NO	YES

Significance levels: * : 1% : 5% : 10%.

Standard errors of the baseline sample are clustered at the country level.

For the counterfactual groups, we are using bootstrap estimate using 100 replications.

Table A6: Treatment effects for green, renewable-energy, and fossil-fuel technology innovation ratios *excluding GDP and energy prices*.

	World	Europe	Top Green
	(1)	(3)	(6)
Panel A: GREEN/FF			
Diff-in-diff	-1.516***	-1.422**	-1.760**
se	(0.340)	(0.565)	(0.685)
Panel B: GREEN/Total			
Diff-in-diff	-0.155***	-0.150***	-0.168***
se	(0.0212)	(0.0440)	(0.0282)
Panel C: REN/FF			
Diff-in-diff	-0.856***	-0.897*	-0.981
se	(0.248)	(0.511)	(0.615)
Panel D: REN/Total			
Diff-in-diff	-0.0432	-0.0446	-0.0419**
se	(0.0264)	(0.0316)	(0.0201)
Panel E: FF/Total			
Diff-in-diff	0.211***	0.194***	0.197***
se	(0.0263)	(0.0582)	(0.0394)
Country FE	YES	YES	YES
Year FE	YES	YES	YES
Interaction	YES	YES	YES

Significance levels: : 1% : 5% : 10%.

Standard errors clustered at the country level.