Energy Policy 128 (2019) 539–552

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Impact of domestic energy-efficiency policies on foreign innovation: The case of lighting technologies

Yeong Jae Kim[a,*,1], Marilyn Brown[b,2]

[a] Tyndall Centre for Climate Change Research, University of East Anglia, UK
[b] Georgia Institute of Technology, School of Public Policy, USA

ARTICLE INFO

JEL Codes:
Q55
Q54
O33

Keywords:
Economics of Innovation
International Technology Diffusion
Negative Binomial Model

ABSTRACT

Fostering the global development of low-carbon technology is crucial to mitigating greenhouse gas emissions. This paper analyzes the effect of energy-efficiency policies on lighting patenting between 1992 and 2007, using data for 19 OECD countries. We examine levels of energy-efficiency RD&D expenditures (representing a technology-push approach) and the stringency of energy-efficiency performance standards (representing a demand-pull approach). We find strong correlational evidence that both domestic demand-pull and technology-push policies positively affect domestic lighting patenting. We also provide strong correlational evidence that the demand-pull policy positively affects foreign lighting patenting; however, the technology-push policy does not. These findings suggest that demand-pull policies can help to transform international markets for low-carbon technology innovation, and they underscore the importance of the often-overlooked international dimension of domestic energy-efficiency policies. To the extent that our findings are generalizable, our research suggests that governance processes that strengthen energy performance standards and steady investment in RD&D could spur energy innovation in industrialized nations across the world.

1. Introduction

A recent U.S. National Academies report suggests that feedback forces could push the Earth System toward a self-reinforcing condition of continued global warming (Steffen et al., 2018). Constraining global temperature to well below 2 °C above pre-industrial levels will require developing low-carbon energy technologies and deploying them with well-designed energy and environmental policy instruments (Brown and Sovacool, 2014).

To design effective energy and environmental policy instruments, ex-post econometric policy evaluation is important as it reveals the consequences of policy instruments (e.g., innovation). A significant body of research has examined the impact of energy and environmental policy on technological innovation by using patent data (Carrión-Flores and Innes, 2010; Costantini et al., 2015; Verdolini and Galeotti, 2011; Noailly and Ryfisch, 2015). It has documented a positive relationship between policy and technological innovation that is known as the "policy inducement effect" (Brunnermeier and Cohen, 2003; Jaffe and Palmer, 1997; Johnstone et al., 2010; Popp, 2002). Specifically, these studies have investigated a significant impact of domestic policies on domestic environmental innovation. However, few studies have examined international technology diffusion in response to policy instruments.

An initial effort to expand the impact of domestic policy on domestic technological innovation was undertaken by Lanjouw et al. (1996) who analyzed the effect of domestic policy on foreign innovation. They conclude that strict vehicle emission regulations in the United States (U.S.) spurred innovation in Japan and Germany. Popp (2006) found that strengthening U.S. standards led to more patenting in the U.S., but not internationally. Subsequently, Popp et al. (2011) identified a positive correlation between domestic and foreign regulation and innovation, and others have found that foreign policies affect cross-border innovation diffusion (Dechezleprêtre and Glachant, 2014; Dechezleprêtre et al., 2015). Building on the stream of literature on the international diffusion of low-carbon technologies (Dechezleprêtre and Glachant, 2014; Dechezleprêtre et al., 2013a; Peters et al., 2012), this paper tests the impact of domestic energy-efficiency policies on foreign patenting within the empirical context of lighting technologies. We

* Corresponding author.
E-mail addresses: y.kim@uea.ac.uk (Y.J. Kim), marilyn.brown@pubpolicy.gatech.edu (M. Brown).
[1] Permanent Address: Zuckerman Institute for Connective Environmental Research, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK.
[2] Permanent Address: DM Smith 312, 685 Cherry Street, Atlanta, GA 30332-0345, USA.

https://doi.org/10.1016/j.enpol.2019.01.032
Received 9 July 2018; Received in revised form 3 January 2019; Accepted 14 January 2019
0301-4215/

pose the following inquiries: First, what role do these domestic demand-pull and technology-push policies play in inducing compact fluorescent lamps (CFLs) and light-emitting diodes (LEDs) patenting? Second, does domestic demand-pull and technology-push policies affect foreign lighting patenting?

The rest of the paper is organized as follows. Section 2 introduces background information and relevant theories. Section 3 describes the dataset construction. Section 4 describes the empirical methodology and econometric models. Findings are discussed in Section 5, and in Sections 6 and 7 we discuss conclusions and policy implications.

2. Background

Lighting accounts for about 10% of the total electricity consumed in the U.S.[3] According to one International Energy Agency (IEA)'s report, the potential amount of electricity that could be saved in building lighting by 2030 is equivalent to the entire electricity consumed in Africa in 2013.[4]

Reflecting on the history of technological development in lighting, light bulb technologies have continuously developed to better serve consumer needs.[5] An incandescent light bulb is a device that emits light when an electric current passes through a filament until it glows (Zhu and Humphreys, 2012). The invention of the first incandescent light bulb by Thomas Edison and other precursors was the foundation upon which subsequent incandescent light bulb designs were based (Friedel and Israel, 2010). It has served as the single most popular lighting technology for more than 100 years. The price of incandescent light bulbs has dropped continuously, and their performance has improved, but their energy-efficiency remains low.

Unlike an incandescent light bulb, CFLs generate invisible light that excites a fluorescent coating inside a tube and then emits visible light when an electric current passes through the tube's argon and mercury vapor (Azevedo et al., 2009). The original fluorescent lamp technology was developed in the late 1940s. A CFL looks like an incandescent light bulb, but it is more energy efficient and lasts ten times longer. Although somewhat more expensive to buy than incandescents, CFLs are cost-effective options in many locations where lights are used regularly. Beginning in the late 1980s, utilities engaged in demand-side management to increase consumers' adoption of CFLs but faced technical difficulties. In the late 1980s and early 1990s, CFLs were bulky, and their color rendition was inferior to incandescent light bulbs. In general, consumers were reluctant to buy CFLs where higher up-front costs were needed to achieve lower operating costs compared to incandescent light bulbs (Ledbetter et al., 2013).

In contrast, LEDs are semiconductor devices that produce light; in a light bulb, red, green, and blue LEDs combine to make white light (Zhu and Humphreys, 2012). There are three types of LED lights: solid-state lighting (SSL), organic light-emitting diodes (OLEDs), and light-emitting polymers (LEPs). They emit little heat, which makes them more energy efficient. LEDs were first developed in 1961; they have recently emerged as viable alternatives to incandescent light bulbs because of their greater energy efficiency, longer lifespans, and declining costs with mass production. Since 2011, the price of LED bulbs has dropped by 28–44% per year, depending on lumen output (Gerke et al., 2014). On a life-cycle basis, CFLs and LEDs are more cost-effective than incandescent light bulbs. According to a study by the U.S. Department of Energy (DOE), if between 2013 and 2030 conventional light bulbs are replaced with LEDs where currently feasible the U.S. would reduce its electricity for lighting by about 50% in 2030 (Navigant Consulting, 2014). At the same time, significant greenhouse gas reductions would result.[6]

Table 1 compares key characteristics of incandescent light bulbs, CFLs, and LEDs. From a life-cycle perspective, LEDs are the most cost-effective option among the three technologies; however, they also have the highest upfront cost, which is their main obstacle to high market penetration (National Research Council, 2005; Navigant Consulting, 2006). To expand market diffusion, effort is needed to further reduce the upfront cost of LEDs (Azevedo et al., 2009).

Several factors affect energy innovation. First, the "Induced Innovation" hypothesis argues that changes in the relative prices of the factors of production can spur innovation within an industry (Hicks, 1932).[7] Second, technological change can be induced by policy intervention (Jaffe et al., 2003), thereby creating a demand for clean technologies, which in turn motivates environmental innovation. Economic theory shows that market-based environmental policies are more cost-effective than command-and-control environmental policies to encourage development of low-carbon technologies (Jaffe et al., 2002; Popp et al., 2010).

Literature on policy-induced technical change has distinguished between "technology-push" and "demand-pull" forces (Dosi, 1982; Nemet, 2009). Technology-push is a supply-side driven policy inducement effect motivated by technological advancements (Bush, 1945). Substantial research and development (R&D) efforts are needed to advance technologies toward mature stages of the innovation lifecycle (Rennings, 2000). On the other hand, demand-pull is a demand-side driven policy inducement effect that is motivated by the anticipation of growing consumer markets. Demand-pull can also be a key driver of technical change (Schmookler, 1966). A robust body of literature has shown that both "technology-push" and "demand-pull" can induce technical change, and they closely interact with each other (Mowery and Rosenberg, 1979).

From the firm's perspective, environmental and energy innovation is risky, as future return on investment is uncertain (Jaffe et al., 2002). To encourage the investment of firms in environmental and energy innovation, continuous policy support is crucial to reduce investment risk. For example, a firm may require R&D support from the government to enable infant technology to mature (Rennings, 2000) that would not have been realized otherwise. From the consumer's perspective, the price of LEDs has declined sharply over the past few years and in terms of quality, LEDs last longer and provide better light today compared with earlier LED models. Therefore, LEDs are a more cost-effective option for consumers. Although there are still several barriers that relate to the global uptake of LEDs, more consumers have started to buy LEDs than in the past (IEA, 2018). This demand increase will likely spur continuous innovation among firms, as it reduces the uncertainty of R&D investment by creating new markets and spin-off products. At the same time, energy-efficiency standards can create demand for environmental and energy innovation, and firms innovate themselves to produce more energy-efficient goods and services (Vollebergh and van der Werf, 2014), which initiate a virtuous cycle.

Several energy-efficiency lighting policies coexist in many countries. Japan initiated the Top Runner Program in 1998 to improve the energy efficiency of end-use products. Unlike the previous mandatory energy-efficiency programs in Japan, the Top Runner program was created in response to the Kyoto Protocol,[8] which was adopted in Japan on December 11, 1997, to achieve greenhouse gas emissions targets (i.e., a 6% reduction by 2008–2012 in comparison to the 1990 baseline level). In the case of fluorescent lighting, the efficiency standard was set

[3] https://www.eia.gov/tools/faqs/faq.php?id=99&t=3.

[4] https://www.iea.org/statistics/relateddatabases/worldenergystatisticsandbalances/.

[5] https://energy.gov/articles/history-light-bulb.

[6] CFLs and LEDs do contain hazardous materials such as lead, copper, and zinc, while incandescent light bulbs do not (Lim et al., 2013).

[7] For an empirical analysis, Newell et al. (1999) developed a methodology for testing the hypothesis by estimating a product characteristic of household appliances.

[8] http://unfccc.int/kyoto_protocol/items/2830.php.

Table 1
Comparison of three lighting technologies.

	LED	Compact Fluorescent	Incandescent
Upfront cost	$8	$2	$1
Energy	11 W	14 W	60 W
Efficiency*	0.55	0.2	0.05
Lifetime (hours)	50,000	8000	1200
Power @ 6 h/day	66 W h/day	84 W h/day	360 W h/day
Cost per day @ 11 ₵/kW h	0.72 ₵	0.92 ₵	3.96 ₵
Cost per year @ 11 ₵/kW h	$2.64	$3.37	$14.45
Cost for ten years @ 11 ₵/kW h (discount rate: 7%)	$19.53	$24.86	$106.55

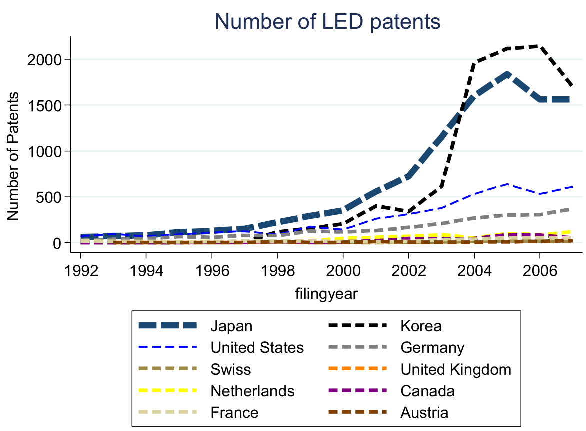

Fig. 1. LED Patent applications per year (1992–2007).

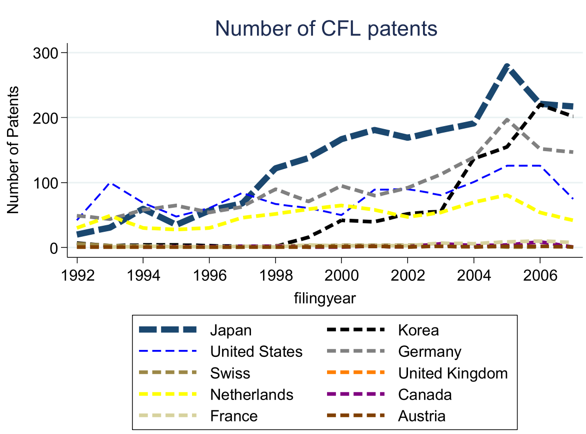

Fig. 2. CFL Patent applications per year (1992–2007).

to the most efficient product in the market. Therefore, it was effective to eliminate the low energy-efficient products from the market and increase the average energy efficiency of the products (Grubler and Wilson, 2014). Also, the Light for the 21st Century Project in Japan began in 1998 and spurred the innovation of the high-efficient ultraviolet (UV) LED and phosphor systems.

In the U.S., the most significant energy policy legislation since the Energy Policy Act of 1992 is the Energy Policy Act of 2005. Key pieces of this legislation were manufacturer and consumer tax incentives and minimum energy-efficiency standards for 16 products. The Energy Policy Act of 2005[9] provided a tax deduction for energy-efficient commercial buildings beginning in 2006. Inventors have incentives to produce more energy-efficient products to meet the requirements. The Energy Policy Act of 2005 also set new minimum efficiency standards for several products, and authorized tax incentives for manufacturers.

Similarly, South Korea replaced 40 W fluorescent lamps with 32 W fluorescent lamps in 2004. Afterward, Korea started its LED Lighting 15/30 Dissemination Project in 2006. In 2008, Korea decided to phase out incandescent light bulbs from the market. European Union (EU) policies related to the direct support of SSL such as EU eco-design Regulation 244/2009 are somewhat belated in comparison to the first-mover countries: Japan, Korea, and the U.S. The European Lamp Companies Federation called for better policies supporting SSL (European Lamp Companies Federation, 2011).

3. Dataset construction

To test the impact of domestic energy-efficiency policies on foreign patenting within the empirical context of lighting technologies, several datasets are constructed. To measure the dependent variable, we collected patent data from the European Patent Office (EPO)/Organization for Economic Cooperation and Development (OECD) World Patent Statistical Database (PATSTAT)[10] to analyze inventive behaviors related to LEDs and CFLs across countries. PATSTAT contains patents filed in more than eighty patent offices and includes more than sixty-five million patent applications and thirty million granted patents. However, PATSTAT has a significant missing inventor/applicant-country information problem, especially for Japanese patents. To overcome this challenge, we filled in the missing country information from two patent families (i.e., simple [DOCDB] and extended [INPADOC]), as well as the individuals' names and identification. For the rest, we use the common first name to fill in the missing country information. After that, we drop the remaining missing values (fewer than 5% of the total patents). In order to better count the number of patents by country, we alternatively use the fractional count in the robustness checks. This method improves the international comparability of patent counts (Dernis and Guellec, 2001). The Technical Appendix reports the number of patents by country of the first-inventors between 1992 and 2007 for both LEDs and CFLs. Japan is the leading country in patenting, followed by Korea, the U.S., and Germany. We also assess the number of patents by fractional country counts by the extended patent family.

To retrieve relevant patents, we rely on two definitions of lighting technologies. First, the OECD and EPO (Organization for Economic Cooperation and Development OECD, 2012) identified "technologies related to climate change mitigation and adaptation." This category includes lighting technologies that map into the international patent classification (IPC) codes. For example, it identifies LEDs as "H05B" or "F21K"[11] and CFLs as "H01J 61." Dechezleprêtre et al. (2013b) used the same IPCs to discern between clean and dirty technologies. Since these IPCs do not capture the recent development of OLED technologies, we also add additional IPCs related to LEDs (Simons and Sanderson, 2011; Sanderson and Simons, 2014). An Appendix provides the description of IPCs related to lighting technologies.

In order to measure the impact of energy-efficiency policy on inventive activities, there are several challenges. First, patent data is not a perfect measure of technological innovation. However, Griliches (1990) argues that patent data is a good proxy variable for innovative activity. Additionally, patent data are the most frequently used metrics to measure the creation of new knowledge (Schmookler, 1962, 1966; Griliches, 1990; and Hall et al., 2001; Scherer, 1965). While the reliability of patents as a measure of innovation output continues to be

[9] http://energy.gov/savings/energy-efficient-commercial-buildings-tax-deduction.

[10] PATSTAT Oct 2013 edition. PATSTAT data comes from the Enterprise Innovation Institute at Georgia Institute of Technology.

[11] H05B33: Electroluminescent light sources (LED), F21K9: Electric lamps using semiconductor devices as a light-generating element, for example by using light emitting diodes (LED).

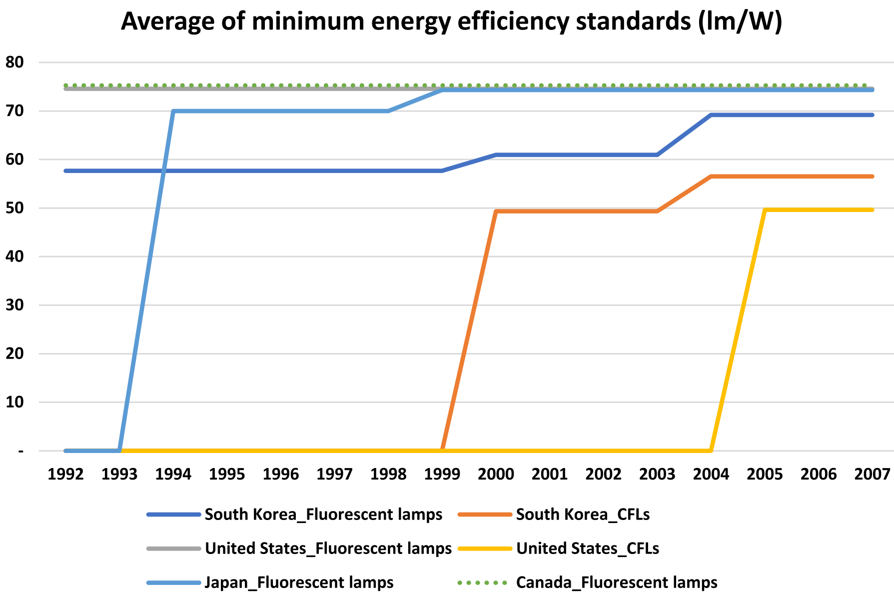

Fig. 3. Average of minimum energy efficiency standards (lm/W). Notes: 1. Japan's Top Runner Program is not Minimum Energy Performance Standards (MEPS). (e.g., 1994–1997: max target). 2. Amendments 9 in 2006: The stringency of MEPS was tightened for the following products: Fluorescent Lamp Ballast(July 2006). Ballast is out of the scope of this paper. 3. Energy Policy Act of 2005 Sets New Ballast Efficiency Standards: new minimum ballast efficacy factor (BEF) standards (It is not considered in this analysis.). 4. In the United States, the Energy Independence and Security Act of 2007 was signed into law in December 2007. It plans to phase out the use of incandescent light bulbs by 2014, and improve lighting efficiency by more than 70% by 2020.

Table 2
Summary statistics.

Variables	Units	Mean	Std. Dev.	Min	Max
Patent counts per country	Number	90.68	274.52	1	2145
Fractional patent counts per country	Number	66.70	216.08	1	1886
Patent transfer counts per country	Number	18.76	79.73	1	1649
Fractional patent transfer counts per country	Number	16.11	76.38	1	1536
MEPS florescent lamps	Lm/W	20.87	32.51	0.00	75.25
MEPS CFL	Lm/W	2.88	11.95	0.00	56.50
RD&D expenditures	Million USD	23.09	40.27	0.00	231.48
Average Electricity Price of Industry and Household	USD/KWh	109.53	41.85	45.00	247.26
Growth (Electricity consumption)	Percentage Change	2.05	3.15	− 12.63	11.88
Growth (GDP)	Percentage Change	0.05	0.03	− 0.02	0.18

Table 3
Effects of domestic policies on domestic patenting.

No. of patents	(1) LED Negative Binomial	(2) LED Poission	(3) LED Poission IV	(4) CFL Negative Binomial	(5) CFL Poission	(6) CFL Poission IV
MEPS	0.0269***	0.0363***	0.0296***	0.0236***	0.0260***	0.0255***
	(0.00433)	(0.00648)	(0.00629)	(0.00303)	(0.00424)	(0.00407)
MEPS_CFL	0.0194***	0.00938*	0.0263**	0.00392	0.00356	0.00631
	(0.00663)	(0.00513)	(0.0120)	(0.00367)	(0.00336)	(0.00468)
$RD\&D_{t-1}$	0.00489***	0.00357***	0.0123***	0.00250**	0.00245**	0.00361*
	(0.00180)	(0.00130)	(0.00340)	(0.00107)	(0.000979)	(0.00188)
Electricity Price	0.0117***	0.00463**	0.00701***	− 0.000127	0.000106	0.00122
	(0.00143)	(0.00216)	(0.00254)	(0.00132)	(0.00148)	(0.00111)
Growth (Electricity consumption)	− 0.00964	− 0.0279	− 0.124***	− 0.0225	− 0.0286*	− 0.0368*
	(0.0192)	(0.0208)	(0.0416)	(0.0140)	(0.0156)	(0.0222)
Growth (GDP)	5.927*	1.008	11.14*	− 0.209	− 1.846	− 0.0867
	(3.206)	(4.506)	(6.639)	(2.507)	(2.654)	(2.469)
Observations	207	207	207	143	143	143
Year FE	YES	YES	YES	YES	YES	YES
Country FE	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Table 4
Effects of domestic policies on foreign patenting.

No. of patent transfer	(1) LED Negative Binomial	(2) LED Poission	(3) LED Poission IV	(4) CFL Negative Binomial	(5) CFL Poission	(6) CFL Poission IV
MEPS	0.0217***	0.0278***	0.0216**	0.0197***	0.0181***	0.0220***
	(0.00464)	(0.00734)	(0.00867)	(0.00488)	(0.00408)	(0.00641)
MEPS_CFL	0.0153**	0.00979	0.0177*	0.00288	0.00227	− 0.000881
	(0.00687)	(0.00821)	(0.00968)	(0.00583)	(0.00567)	(0.00749)
$RD\&D_{t-1}$	0.00338*	0.00284	0.00944**	0.00312*	0.00257*	0.000188
	(0.00179)	(0.00261)	(0.00387)	(0.00164)	(0.00150)	(0.00542)
Electricity Price	0.00304***	− 0.00170	− 0.000362	0.000639	0.000369	0.000281
	(0.00118)	(0.00282)	(0.00264)	(0.00175)	(0.00134)	(0.00164)
Growth (Electricity consumption)	− 0.0143	− 0.00866	− 0.0798	− 0.0304	− 0.0244	− 0.0206
	(0.0164)	(0.0502)	(0.0616)	(0.0270)	(0.0195)	(0.0311)
Growth (GDP)	3.850	4.104	11.20	2.675	2.039	1.100
	(2.756)	(8.941)	(8.071)	(4.170)	(3.393)	(3.995)
Observations	1081	1081	1081	659	659	659
Year FE	YES	YES	YES	YES	YES	YES
Country FE	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

debated, patent count at the firm, industry, and country levels can be a useful measure of innovative output in energy technology.[12] Second, energy-efficient technological improvements could be a small portion of inventive activities, so it is highly likely that we cannot find any statistically significant results. However, this is not a major concern in LED and CFL patents. On the contrary, the number of incandescent light bulb patents[13] (104) has been very small since 1976. So we omitted the incandescent light bulb from the analysis.

Fig. 1 shows LED patent applications per year. Japanese inventors are the leaders in this arena, followed by Korean and U.S. inventors, respectively. The number of LED patent applications in Japan grew continuously starting in about 1996 and in the U.S. starting in about 1997. Korean inventors filed more LED patent applications than Japanese inventors after 2003. Fig. 2 shows a CFL patent applications per year. Japanese inventors lead CFL patenting while Korean, United States, and Germany inventors followed.

To measure demand-pull policies, we use the stringency of energy efficiency policies. As we explained earlier, diverse policy instruments come into play jointly. Finding data that are comparable across countries to measure these policy instruments' stringency is challenging. One way to measure their stringency across countries is to use the average of minimum energy efficiency standards as a proxy for the level of demand-pull policies. This approach is similar to measuring the building codes' stringency using the U-values (Noailly, 2012). Fig. 3 shows the evolution of the minimum energy efficiency standards for fluorescent lamps and CFLs across major countries. The higher the minimum energy efficiency standards, the more stringent the policy instruments. The Technical Appendix provides a more detailed description of each policy instrument, scope, and the sources. It is expected that the sign of the stringency energy efficiency policies is positive in econometric models.

To measure technology-push policies, we use one-year lagged Research Development & Demonstration (RD&D) expenditure as a proxy variable (Dechezleprêtre and Glachant, 2014). RD&D expenditure[14] for nineteen countries[15] is included in IEA's energy technology research and development database.[16] Ideally, we need lighting energy efficiency RD&D expenditures, but it is not possible to use them due to missing data. So residential and commercial buildings, appliances, and equipment RD&D expenditures are the most granular data that is comparable across countries. It is expected that the sign of RD&D expenditures is positive.

We include following control variables in econometric models. Control variables are expressed as followings[17]: the growth of household electricity consumption, electricity price,[18] and the growth of Growth Domestic Product (GDP). The growth of industry and household electricity consumption data[19] comes from IEA's Energy Balances Database.[20] Electricity price data[21] comes from industry and residential end-user prices, which can be obtained from IEA's Energy Prices and Taxes Database. We eliminated duplicates and restricted data to the span of time between 1992 and 2007. The growth of GDP data comes from the OECD database.[22] Table 2 shows summary statistics of main variables in our econometric models. The first four rows are dependent variables and the remaining are independent variables.

4. Empirical methodology

First, we estimate the effect of domestic demand-pull and technology-push policies on domestic lighting patenting. The dependent variable is the number of patent application in country i in year t. An econometric model is constructed as follows:

[12] A discussion of the relationship between patent data and energy innovation output is well documented in Popp's (2005) paper.

[13] The IPC code for incandescent light bulb is "F21H."

[14] Total RD&D in Million USD (2016 prices and exchange rates) of the energy efficiency. RD&D covers basic research, applied research, experimental development, and demonstration of a prototype of a technology.

(footnote continued)
https://www.iea.org/media/statistics/questionnaires/RDDQuestionnaire.pdf.

[15] Nineteen countries are: Japan, United States, Canada, Korea, Germany, United Kingdom, Netherlands, Switzerland, France, Sweden, Norway, Italy, Finland, Australia, Austria, Belgium, Denmark, Spain, and New Zealand.

[16] http://wds.iea.org/WDS/ReportFolders/ReportFolders.aspx.

[17] We restrict to the nineteen countries in order to match control variables.

[18] USD PPP/unit.

[19] The growth rate is calculated by (Post consumption/current consumption) ˆ (1/9) − 1.

[20] http://www.iea.org/statistics/topics/energybalances/.

[21] The missing data are interpolated.

[22] https://stats.oecd.org/index.aspx?queryid = 60702#.

$$N_{i,t} = \beta_{11} + \beta_{21}MEPS_{i,t} + \beta_{31}MEPS\_CFL_{i,t} + \beta_{41}RD\,\&\,D_{i,t-1} + \beta X_{i,t} + \alpha_t + \gamma_i + \varepsilon_{i,t} \quad (1)$$

Where $i = 1,\ldots,19$ refers to the country and $t = 1992,\ldots,2007$ refers to time. **MEPS** is the average minimum energy efficiecny standards of fluorescent lamps. **MEPS_CFL** indicates the average minimum energy efficiency standards of CFLs. **RD&D** refers to residential and commercial buildings, appliances, and equipment RD&D expenditures. ***X*** are control variables: **ELEC** refers to the growth of industry and household electric consumption. **PRICE_ELEC** refers to the industry and household electricity price data. **GDP_GR** refers to the growth of Gross Domestic Product. α and γ each refer to time and country fixed effects. In addition, all the remaining errors are captured in the ε.

Second, we estimate the effect of the domestic demand-pull and technology-push policies on the number of foreign patent applications related to energy-efficient innovations in lighting technologies. The dependent variable is the number of patent granted in country *i* that are filed in country *j* in year *t*.

$$N_{i,j,t} = \beta_{12} + \beta_{22}MEPS_{i,t} + \beta_{32}MEPS\_CFL_{i,t} + \beta_{42}RD\,\&\,D_{i,t-1} + \beta X_{i,t} + \alpha_t + \gamma_i + \varepsilon_{i,t} \quad (2)$$

Where $i, j = 1,\ldots,19$ refers to the country and $t = 1992,\ldots,2007$ refers to time. **MEPS** is the average minimum energy efficiecny standards of fluorescent lamps. **MEPS_CFL** indicates the average minimum energy efficiency standards of CFLs. **RD&D** refers to residential and commercial buildings, appliances, and equipment RD&D expenditures. ***X*** are control variables: **ELEC** refers to the growth of industry and household electric consumption. **PRICE_ELEC** refers to the industry and household electricity price data. **GDP_GR** refers to the growth of Gross Domestic Product. α and γ each refer to time and country fixed effects. In addition, all the remaining errors are captured in the ε.

To estimate the econometric models, we prefer the negative binomial model to the Poisson model due to over-dispersion issues. We also use conditional maximum likelihood Poisson with fixed effects (Hausman et al., 1984). RD&D expenditure may generate a simultaneity issue because they are inputs of the innovation processes. To account for the potential endogeneity issue of RD&D expenditures, we use an instrument variable (IV) approach similar to Dechezleprêtre and Glachant (2014). We use RD&D expenditures in transport energy efficiency in the same country and year, thereby satisfying two conditions of an instrument's validity. First, they do not directly affect the number of lighting energy efficiency patents because they are different from a technological point of view. Second, they are positively correlated with appliance energy efficiency RD&D expenditure, as they are both energy efficiency RD&D expenditures. To check the model's robustness, we use the number of patents by fractional country counts by the extended patent family as a dependent variable.

5. Results

5.1. Effect of domestic policies on domestic patenting

Table 3 shows the effects of domestic policies on domestic patenting. It indicates that the demand-pull policies represented by MEPS are statistically significantly positive in both technologies. Note that the magnitude of LEDs' MEPS coefficient is greater than that of the CFLs' coefficients. The results provide evidence of a positive relationship between domestic demand-pull energy efficiency policies on domestic lighting patenting. It also shows that the technology-push policies represented by $RD\&D_{t-1}$ expenditures are statistically significantly positive in LED technology. Although the effect of technology-push policies is not robust due to various specifications in CFL technology, the overall effect of technology-push policies on domestic patenting is positive. Columns (1)-(3) support the induced innovation hypothesis that rising energy prices induce innovation, but columns (4)-(6) do not.

To check the robustness of the models, we re-estimate equations presented in Eqs. (1) and (2) using the number of fractional patent count as an alternative dependent variable. The Technical Appendix shows the estimation results. We find consistent results with the main findings. All in all, our estimation results are robust to the various model specifications.

5.2. Effect of domestic policies on foreign patenting

Table 4 shows the estimation results of the effects of domestic energy efficiency policies on foreign lighting patenting. It verifies domestic demand-pull policies have a statistically significant positive effect on the number of technology transfer. The overall magnitude of coefficients is smaller than the size of coefficients in Table 3. The notable difference in Table 4 is that the effect of technology-push polices on the number of patent transfer is not statistically significant.

To check the robustness of the models, we re-estimate the econometric model. We find the consistent results while the Poission IV approach in Appendix is statistically significant at the 10% level. Overall, the estimation results are robust except one model specification.

6. Discussion

Based on the estimation results, we find evidence that establish a strong correlation. First, we use patent data to examine the effect of domestic demand-pull and technology-push policies on domestic innovation activity in lighting technologies between 1992 and 2007. We find that both domestic demand-pull and technology-push policies positively affect domestic lighting patenting that is consistent with previous studies such as Dechezleprêtre and Glachant (2014) and Peters et al. (2012).

Second, we estimate the effect of domestic demand-pull and technology-push policies on foreign lighting inventive activities. The estimation results produce strong evidence that domestic demand-pull policies positively affects foreign lighting patenting in the fields of CFLs and LEDs. However, we cannot find any evidence to prove that domestic technology-pull policies affect foreign lighting patenting.

Although we cannot directly compare our results to Dechezleprêtre and Glachant (2014) due to different model specifications, our findings are consistent with the literature on directed technological change in economics literature. If we ignore the international dimension of lighting innovation by only looking at the effect of domestic energy policy on domestic innovation, we underestimate energy policies' overall impact on innovation.

As Peters et al. (2012) pointed out, it is arguable whether policymakers will continue to support demand-pull policies if they gain knowledge of spillover effects, which undermine domestic firms' competitiveness. From a domestic perspective, it is rational to focus more on technology-push policies than on demand-pull policies. However, it is crucial to form supranational demand-pull policies to offset the disincentives of domestic demand-pull policies. For example, the United Nation's new initiative[23] in May 2018 to help emerging and developing countries estabilish a minimum energy efficiency standards for lighting can help accelerate the transition to more energy efficient LEDs.

The role of energy prices is only statistically significant for the estimation of domestic policies' effects on domestic LED patenting. We cannot find other evidence to support the induced innovation hypothesis. One possible explanation is similar to Noailly's (2012) building sector argument. The explanation is that economic incentives may have a small and nonsignificant effect because light bulbs are used in buildings due to the presence of the principal and agent problem. Hence, it is important to strengthen RD&D support and minimum

[23] https://www.nrdc.org/experts/nrdc/uns-new-global-initiative-accelerate-phase-out-incandescents-and-shift-led-bulbs.

energy efficiency standards rather than adjusting energy prices to spur lighting innovation in the specific case of lighting technologies.

Foreign inventors have incentives to file patent applications for various reasons. Considering the size of the foreign market, it is plausible that foreign inventors filed patent applications to protect their intellectual property with other major patent offices at the same time. In addition, foreign inventors often are motivated to protect their intellectual property rights for reasons such as licensing or selling the invention, good image for company's market value, or preempt lighting market.

It is also worth noting that the qualitative component of policies was proxied by the average of minimum energy efficiency standards in the regression analysis. For example, it is well known that the dynamic and nimble energy-efficiency standard adjustments of the Top Runner Program were a pivotal factor in spurring the energy-efficiency improvement of the end-use products (Grubler and Wilson, 2014). Thus, we cannot overemphasize the importance of policy design and the involvement of diverse stakeholders in the policy revision process.

One limitation of this study is scope and period of the study. Although we have verified the consistent findings if a different subperiod was chosen (e.g. 1995 and 2007) as a sensitivity test, but we cannot conduct additional tests beyond the geographical areas of study and time window due to the lack of available data (e.g. energy efficiency standards) and patent data truncation due to lags in PATSTAT. Further study should extends research on the geographic scope and number of periods. We are careful not to over-generalize from this study, but our results do have a clear policy implication: the importance of the international dimension of domestic demand-pull policies.

Future work should be also focused on firms' behaviors in response to policy instruments. Differences might exist across multinational firms as well as across countries in the way policy affects firms' behaviors. One interesting research avenue could be examination of which firms are most active in LED patenting, big or small. For example, Sorra,[24] a start-up LED firm, received about $6 million from The Energy Department's Advanced Research Projects Agency-Energy (ARPA-E) and might soon actively file patent applications. Additionally, it is worth drawing our attention to a cross-database comparison because various patent databases show various landscapes, particularly Chinese patent databases written in English or Chinese. For example, Chinese, Japanese, Taiwanese, and South Korean inventors filed a number of LED patent applications in the Chinese patent database in that order, which is different from the order in the PATSTAT database (Gallagher, 2014).

7. Conclusions and policy implications

This paper identifies the effect of domestic demand-pull and technology-push energy-efficiency policies on domestic and foreign patenting in the field of lighting technologies. We find strong correlational evidence linking both domestic demand-pull and technology-push policies with domestic lighting patenting. We also find strong correlational evidence of a significant and positive relationship between domestic demand-pull policy and foreign lighting patenting. This is consistent with a causal relationship, but we cannot eliminate the possibility of a post hoc fallacy. To confirm causality, it is necessary to take into account all other factors that could be responsible for the temporal relationship between both domestic/foreign demand-pull and technology-push policies and domestic/foreign lighting patenting. However, the lack of available data prevents such an assessment.

This paper has a clear policy implication. Policymakers should pay attention to international dimensions of energy-efficiency standard setting because policy and innovation are intertwined in an international domain. To the extent that our findings are generalizable, our research suggests that governance processes that strengthen energy performance standards and steady investment in RD&D could spur energy innovation in industrialized nations across the world. Significant greenhouse gas emission reductions could be a valuable co-benefit.

Acknowledgements

PATSTAT is supported by the Enterprise Innovation Institute at Georgia Institute of Technology. We acknowledge constructive comments from members of the Climate and Energy Policy Laboratory at Georgia Tech, the Atlanta Conference on Science and Innovation Policy, WORP, the ETH Academy on Sustainability and Technology, 41st IAEE International Conference, 6th World Congress of Environmental and Resource Economists, and members of the Energy Club at Georgia Tech. We have benefited from discussions with Matej Drev, Vivek Ghosal, Erik Johnson, Kaye Husbands Fealing, Pat McCarthy, and Charlie Wilson. I thank Seok Beom Kwon and Elie Ji-Yun Sung for providing helpful guidance on using PATSTAT. The role of Dr. Marilyn Brown in this research was supported by the Brook Byers Institute for Sustainable Systems, Georgia Institute of Technology. The authors are also grateful to two anonymous reviewers for helpful comments. All remaining errors are the responsibility of the authors.

Technical Appendix

See Tables 5–13.

Table 5
Lighting policies across major countries.

Country	Year	Policy	Contents
	2003	S&L R&D Project	2003–2005
U.S.	**2005**	Energy Policy Act of 2005	Solid-State Lighting Program Minimum standards for bare and covered medium screw base self-ballasted CFLs manufactured for use in the U.S.
	2007	The Energy Independence and Security Act of 2007 (EISA)	It began phasing out 100 W incandescent light bulbs in 2012, 75 W in 2013, and 40 & 60 W in 2014, consequentially.
Japan	**1993**	Efficiency standards for fluorescent lamps	The government called for an improvement in energy efficiency by 2000 of 3–7% compared to the level of 1992.
	1998	21st Century Lighting Project	Promoting its semiconductor lighting technology 1998–2002
	1998	Top Runner Program of the Energy Conservation Law	To improve energy efficiency of end-use products e.g.) Fluorescent lights: 16.6% increase in lm/W (FY 1997 vs. FY 2005)

(continued on next page)

[24] https://arpa-e.energy.gov/?q=slick-sheet-project/ammonothermal-growth-gan-substrates-leds.

Table 5 (*continued*)

Country	Year	Policy	Contents
	2005	Tax incentive	Tax incentive item in December 2005 (LED)
	2001	Semiconductor lighting national program	1993–1996, 1999–2000, 2001
South Korea	**2004**	Replacement of 40 W fluorescent lamps with 32 W fluorescent lamps	The increase of the MEPS standard (66 lm/W - > 80 lm/W) for 40 W fluorescent lamps in January 2004 accelerated the replacement of 40 W fluorescent lamps with 32 W fluorescent lamps.
	2006	LED Lighting 15/30 Dissemination Project	It aims to increase the share of LED lights to 30% by 2015 (Ministry of Knowledge Economy)

Sources:
U.S. Congress. 109th Congress. (2005, Aug. 8)., Pub. L. 109-58, Energy Policy Act of 2005, Available: http://www.gpo.gov/fdsys/pkg/PLAW-109publ58/pdf/PLAW-109publ58.pdf.
https://www.energystar.gov/ia/products/lighting/cfls/downloads/EISA_Backgrounder_FINAL_4–11_EPA.pdf.
https://www.iea.org/publications/freepublications/publication/light2006.pdf.
http://www.lrc.rpi.edu/education/outreachEducation/pdf/CLE4/AM_FedStateLegislation.pdf.
http://www.ledinside.com/outlook/2015/10/evaluation_of_led_policies_in_japan_india_and_malaysia.

Table 6
International Patent Classification (IPC) related to lighting technologies.

Lighting	Category	Description	Sources
Incandescent	F21H	Incandescent lamp	OECD
H01J 61	Gas- or vapor-discharge lamps (Compact Fluorescent Lamp)	CFL	
LED	F21K9	Electric lamps using semiconductor devices as light generating element, e.g., using light emitting diodes (LED)	
	H05B33	Lighting-Electroluminescent light (LED) sources	(Simons and Sanderson, 2011), OECD
	H01L33/00	Semiconductor devices for light emission, including manufacture and details thereof	(Simons and Sanderson, 2011)
	G09G3/30	Circuits for readable displays using electroluminescent panels	
	G09G3/32	As G09G3/30, using semiconductors	
	G09F9/33	Pixel-based displays using semiconductors	
	H01L 27/15	Solid-state circuitry incorporating semiconductor light-emitting devices	
	G09G3/14	As G09G3/32, but for displaying a single character	

Table 7
Number of patents for both LEDs and CFLs, by country of inventors (1992–2007).

Country	No. of patents	Percent (%)
AT	118	0.33%
AU	42	0.12%
BE	161	0.45%
CA	452	1.26%
CH	138	0.38%
DE	3899	10.83%
DK	22	0.06%
ES	41	0.11%
FI	54	0.15%
FR	447	1.24%
IT	176	0.49%
JP	12,619	35.05%
KR	10,720	29.78%
NL	1521	4.23%
NO	14	0.04%
NZ	5	0.01%
SE	62	0.17%
US	5507	15.30%
Total	35,998	100%

*AT (Austria), AU (Australia), BE (Belgium), CA (Canada), CH (Switzerland), DE (Germany), DK (Denmark), ES (Spain), FI (Finland), FR (France), GB (United Kingdom), IT (Italy), JP (Japan), KR (Korea), NL (Netherlands), NO(Norway), NZ (New Zealand), SE (Sweden), and US (United States).
*Source: http://www.wipo.int/pct/guide/en/gdvol1/annexes/annexk/ax_k.pdf.

Table 8
Scope and description of policy stringency.

Country	Year	Description	Scope	Source
South Korea	1992–1999	In 1992 the Ministry of Commerce, Industry and Energy (MOCIE) is authorized by the Act to set MEPS levels.	Fluorescent lamps Tubular(20 W and 40 W) and Circular(32 W)	http://www.energyrating.gov.au/sites/new.energyrating/files/documents/200310-rislamps_0.pdf
	2000–2003	Revision notifies "Regulation on Energy Efficiency Labeling and Standards based on the Act Chapter 15 and others of Rational Energy Utilization Act of Korea.	Fluorescent lamps Tubular (20 W, 32 W, and 40 W) and Circular(32 W and 40 W)	http://www.energyrating.gov.au/sites/new.energyrating/files/documents/200310-rislamps_0.pdf
	2004–2007	Revision notifies "Regulation on Energy Efficiency Labeling and Standards based on the Act Chapter 15 and others of Rational Energy Utilization Act of Korea.	Fluorescent lamps Tubular (20 W, 32 W, and 40 W) and Circular(32 W and 40 W)	http://www.kemco.or.kr/nd_file/kemco_eng/MKE_Notice_2010-124.pdf
	2000–2003	The mandatory labeling and MEPS program for CFLs came into force in 2000 under the Law on the Rationalized Use of Energy and is administered by the Korea Energy Management Corporation (KEMCO).	Bare Lamps(10 W < , 10W-15W, 15w >)	http://www.energyrating.gov.au/sites/new.energyrating/files/documents/MEPS_Profile_-_Compact_Fluorescent_Lamps_2005.pdf
	2004–2007	Revision notifies "Regulation on Energy Efficiency Labeling and Standards based on the Act Chapter 15 and others of Rational Energy Utilization Act of Korea.	Compact Fluorescent Lamps(27 W and 36 W)	https://mappingandbenchmarking.iea-4e.org/shared_files/694/download
United States	1992-	Energy Policy Act 1992 sets the MEPS for general service fluorescent lamps.	General service fluorescent lamp	http://www.energyrating.gov.au/sites/new.energyrating/files/documents/200310-rislamps_0.pdf
	2005–2007	Energy Policy Act 2005 sets the MEPS for CFLs.	Bare Lamp and Covered(no reflector)	https://www.energy.gov/sites/prod/files/2016/08/f33/CFL_TP_Final_Rule_2016-8-11_0.pdf
Japan	1994–1998	The Law Concerning the Rational Use of Energy – Effectively Mandatory Minimum Energy Efficiency Standards (1994), has set target efficiency (lamp efficacy)	Commercial, Public, and Residential Lighting	http://www.energyrating.gov.au/sites/new.energyrating/files/documents/200310-rislamps_0.pdf
	1999–2007	Revision of the absolute efficiency improvement(16.6%)	Straight and circular types	https://www.energyefficient.com.au/reports/EWG0398T-main.pdf
Canada	1992–2007	Energy Efficiency Act passed in 1992 and took into effect in 1995.	bi-pin base, U-shaped, recessed double contact base, and single pin base	http://www.energyrating.gov.au/sites/new.energyrating/files/documents/200310-rislamps_0.pdf

Table 9
Effects of domestic policies on domestic patenting (patent family).

No. of patents	(1) LED Negative Binomial	(2) LED Poission	(3) LED Poission IV	(4) CFL Negative Binomial	(5) CFL Poission	(6) CFL Poission IV
MEPS	0.0266***	0.0341***	0.0253***	0.0259***	0.0283***	0.0280***
	(0.00517)	(0.00641)	(0.00614)	(0.00414)	(0.00570)	(0.00569)
MEPS_CFL	0.0188***	0.0112***	0.0232**	0.0103***	0.00785**	0.00960**
	(0.00482)	(0.00380)	(0.00964)	(0.00355)	(0.00347)	(0.00395)
$RD\&D_{t-1}$	0.00459**	0.00345***	0.0120***	0.00322***	0.00297***	0.00375*
	(0.00179)	(0.00122)	(0.00345)	(0.000932)	(0.000934)	(0.00216)
Electricity Price	0.00994***	0.00296	0.00497*	− 0.000650	− 0.000331	0.000687
	(0.00152)	(0.00247)	(0.00296)	(0.00146)	(0.00153)	(0.00122)
Growth(Electricity consumption)	− 0.0227	− 0.0208	− 0.0997***	− 0.0333**	− 0.0378**	− 0.0411**
	(0.0177)	(0.0197)	(0.0328)	(0.0137)	(0.0156)	(0.0188)
Growth(GDP)	6.214*	2.538	13.96**	− 0.602	− 1.342	0.395
	(3.478)	(4.767)	(6.493)	(2.628)	(2.969)	(2.831)
Observations	201	201	201	137	137	137
Year FE	YES	YES	YES	YES	YES	YES
Country FE	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Table 10
Effects of domestic policies on foreign patenting (patent family).

No. of patent transfer	(1) LED Negative Binomial	(2) LED Poission	(3) LED Poission IV	(4) CFL Negative Binomial	(5) CFL Poission	(6) CFL Poission IV
MEPS	0.0203***	0.0250***	0.0178*	0.0206***	0.0230***	0.0286***
	(0.00458)	(0.00750)	(0.0102)	(0.00390)	(0.00522)	(0.00878)
MEPS_CFL	0.0146*	0.00925	0.0217*	0.00317	0.00285	− 0.00487
	(0.00755)	(0.00898)	(0.0116)	(0.00587)	(0.00591)	(0.00974)
$RD\&D_{t-1}$	0.00340*	0.00302	0.0102**	0.00192	0.00208	− 0.00445
	(0.00190)	(0.00281)	(0.00448)	(0.00155)	(0.00168)	(0.00875)
Electricity Price	0.00147	− 0.00358	− 0.00111	− 0.000466	− 0.000704	0.000254
	(0.00135)	(0.00328)	(0.00311)	(0.00150)	(0.00179)	(0.00208)
Growth(Electricity consumption)	− 0.0262	− 0.0315	− 0.0887	− 0.0292	− 0.0331	− 0.0108
	(0.0179)	(0.0582)	(0.0683)	(0.0219)	(0.0282)	(0.0347)
Growth(GDP)	4.513	2.861	7.356	3.201	3.388	2.719
	(3.267)	(10.18)	(8.995)	(3.632)	(4.983)	(5.083)
Observations	903	903	903	534	534	534
Year FE	YES	YES	YES	YES	YES	YES
Country FE	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Table 11
Effects of domestic policies on domestic patenting (1995–2007).

No. of patents	(1) LED Negative Binomial	(2) LED Poission	(3) CFL Negative Binomial	(4) CFL Poission
MEPS	0.216***	0.179***	0.154***	0.151***
	(0.0470)	(0.0432)	(0.0294)	(0.0340)
MEPS_CFL	0.0204***	0.0112*	0.00919***	0.00806***
	(0.00784)	(0.00593)	(0.00258)	(0.00272)
$RD\&D_{t-1}$	0.00365*	0.00287*	0.00317***	0.00291***
	(0.00213)	(0.00169)	(0.000657)	(0.000790)
Electricity Price	0.0107***	− 0.000546	− 3.31e− 05	0.000362
	(0.00138)	(0.00351)	(0.00114)	(0.00129)
Growth (Electricity consumption)	− 0.0150	− 0.0220	− 0.0416***	− 0.0434***
	(0.0201)	(0.0212)	(0.0129)	(0.0135)

(continued on next page)

Table 11 (*continued*)

No. of patents	(1) LED Negative Binomial	(2) LED Poission	(3) CFL Negative Binomial	(4) CFL Poission
Growth (GDP)	10.33***	11.06*	3.135	3.461
	(2.689)	(6.250)	(2.178)	(2.620)
Observations	176	176	122	122
Year FE	YES	YES	YES	YES
Country FE	YES	YES	YES	YES

Robust standard errors in parentheses.
** $p < 0.05$.
*** $p < 0.01$.
* $p < 0.1$.

Table 12
Effects of domestic policies on foreign patenting (1995–2007).

No. of patent transfer	(1) LED Negative Binomial	(2) LED Poission	(3) CFL Negative Binomial	(4) CFL Poission
MEPS	0.188***	0.164*	0.104*	0.102*
	(0.0636)	(0.0886)	(0.0571)	(0.0522)
MEPS_CFL	0.00512	0.00184	0.00175	0.00211
	(0.00740)	(0.00950)	(0.00689)	(0.00643)
$RD\&D_{t-1}$	0.000322	0.000779	0.00279	0.00271
	(0.00204)	(0.00323)	(0.00201)	(0.00183)
Electricity Price	0.00252**	− 0.00467	0.000536	− 6.66e− 05
	(0.00127)	(0.00358)	(0.00203)	(0.00141)
Growth (Electricity consumption)	− 0.00576	0.00807	− 0.0214	− 0.0181
	(0.0165)	(0.0515)	(0.0302)	(0.0204)
Growth (GDP)	6.735**	9.592	6.071	4.113
	(3.066)	(9.758)	(5.108)	(3.730)
Observations	959	959	556	556
Year FE	YES	YES	YES	YES
Country FE	YES	YES	YES	YES

Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Table 13
Correlation Matrix (Full Sample).

	MEPS	MEPS_CFL	RD&D	Electricity Price	Growth(Electricity consumption)	Growth(GDP)
MEPS	1					
MEPS_CFL	0.334	1				
RD&D	0.5709	0.0059	1			
Electricity Price	− 0.2051	− 0.1495	− 0.1339	1		
Growth(Electricity consumption)	0.1381	0.2062	0.0495	− 0.0937	1	
Growth(GDP)	− 0.0525	0.2135	0.005	− 0.36	0.0401	1

See Figs. 4–9.

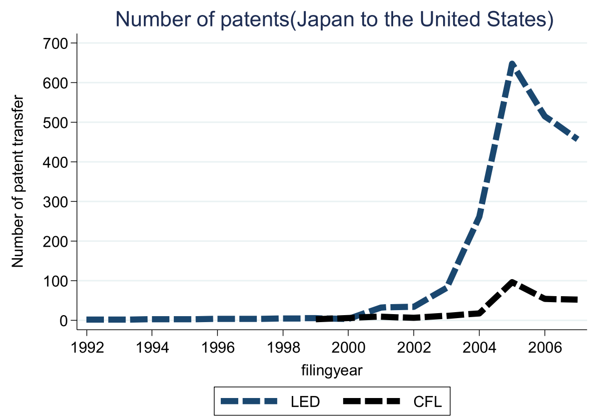

Fig. 4. Number of patent transfer (Japan to the United States).

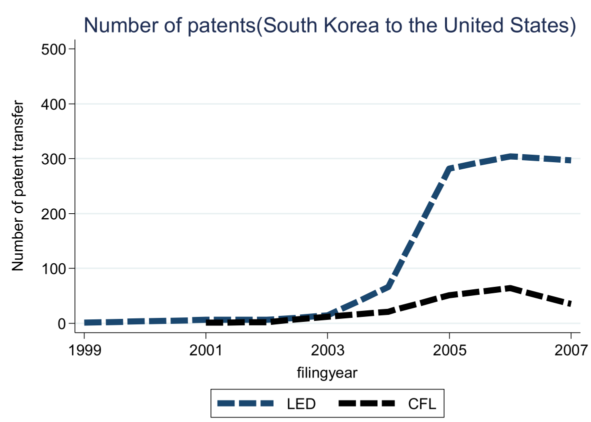

Fig. 5. Number of patent transfer (South Korea to the United States).

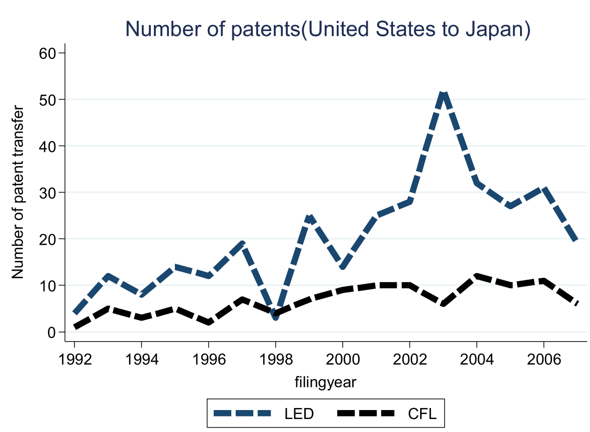

Fig. 6. Number of patent transfer (United States to Japan).

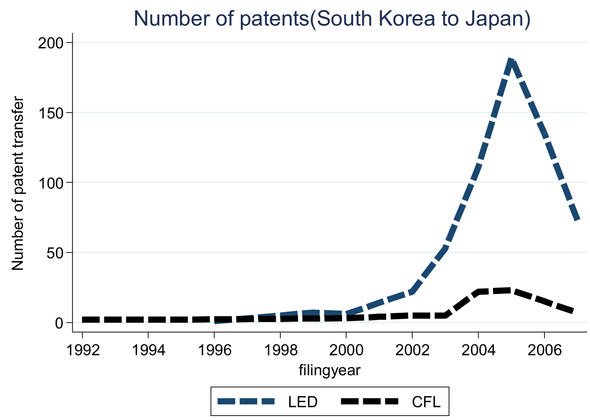

Fig. 7. Number of patent transfer (South Korea to Japan).

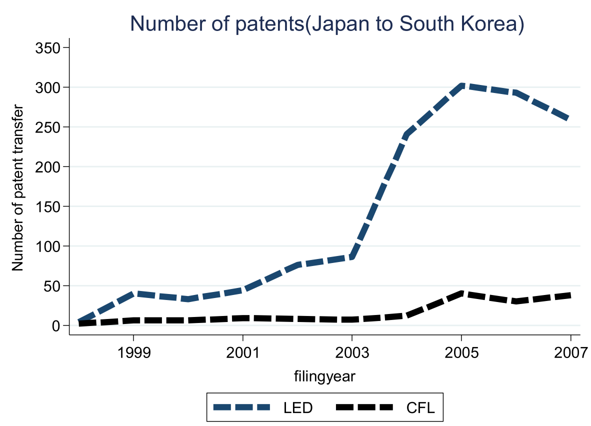

Fig. 8. Number of patent transfer (Japan to South Korea).

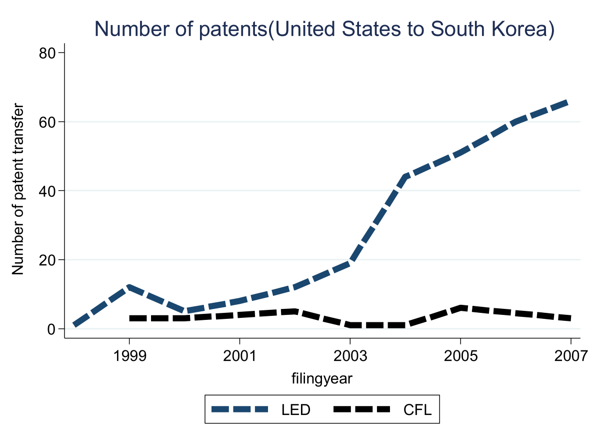

Fig. 9. Number of patent transfer (United States to South Korea).

References

Azevedo, I.L., Morgan, M.G., Morgan, F., 2009. The transition to solid-state lighting white. Proc. IEEE 97 (3), 481–510. https://doi.org/10.1109/JPROC.2009.2013058.

Brunnermeier, S.B., Cohen, M.A., 2003. Determinants of environmental innovation in US manufacturing industries. J. Environ. Econ. Management 45 (2), 278–293. https://doi.org/10.1016/S0095-0696(02)00058-X.

Bush, V., 1945. Science, The Endless Frontier: A Report to the President. Scientific Research and Development United States Government Printing Office.

Brown, M.A., Sovacool, B.K., 2014. Climate Change and Global Energy Security: Technology and Policy Options. The MIT Press, Cambridge, Massachusetts.

Carrión-Flores, C.E., Innes, R., 2010. Environmental innovation and environmental performance. J. Environ. Econ. Manag. 59 (1), 27–42. https://doi.org/10.1016/j.jeem.2009.05.003.

Costantini, V., Crespi, F., Orsatti, G., Palma, A., 2015. Policy inducement effects in energy efficiency technologies. An empirical analysis of the residential sector. In: Green Energy and Technology, pp. 201–232. https://doi.org/10.1007/978-3-319-03632-8.

Dechezleprêtre, A., Glachant, M., 2014. Does foreign environmental policy influence domestic innovation? Evidence from the wind industry. Environ. Resour. Econ. 58 (3), 391–413. https://doi.org/10.1007/s10640-013-9705-4.

Dechezleprêtre, A., Glachant, M., Ménière, Y., 2013a. What drives the international transfer of climate change mitigation technologies? Empirical evidence from PatentData. Environ. Resour. Econ. 54 (2), 161–178. https://doi.org/10.1007/s10640-012-9592-0.

Dechezleprêtre, A., Martin, R., Mohnen, M., 2013b. Knowledge spillovers from clean and dirty technologies: A patent citation analysis. St. Louis. Retrieved from 〈http://prx.library.gatech.edu/login?Url=http://search.proquest.com.prx.library.gatech.edu/docview/1698193161?Accountid=11107〉.

Dechezleprêtre, A., Neumayer, E., Perkins, R., 2015. Environmental regulation and the

cross-border diffusion of new technology: evidence from automobile patents. Res. Policy 44 (1), 244–257. https://doi.org/10.1016/j.respol.2014.07.017.
Dernis, Hélène, Guellec, D., 2001. Using patent counts for cross-country comparisons of technology output. OECD STI Rev. 27, 129–146.
Dosi, G., 1982. Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. Res. Policy 11 (3), 147–162. https://doi.org/10.1016/0048-7333(82)90016-6.
European Lamp Companies Federation, 2011. The European Lighting Industry's Considerations Regarding the need for an EU Green Paper on Solid State Lighting.
Friedel, R., Israel, P., 2010. Edison's Electric Light: The Art of Invention (Revised). Johns Hopkins University Press.
Gallagher, K.S., 2014. The Globalization of Clean Energy Technology: Lessons from China.
Gerke, B.F., Ngo, A.T., Andrea, L., Fisseha, K.S., 2014. The Evolving Price of Household LED lamps: Recent Trends and Historical Comparisons for the US market.
Griliches, Z., 1990. Patent statistics as economic indicators: a survey. J. Econ. Lit. 28 (4), 1661–1707.
Grubler, A., Wilson, C., 2014. Energy Technology Innovation: Learning from Historical Successes and Failures. Cambridge University Press.
Hall, B., Jaffe, A., Trajtenberg, M., 2001. The NBER Patent Citations Data File: Lessons, Insights and Methodological Tools. Cambridge, MA. 〈https://doi.org/10.1186/1471-2164-12-148〉.
Hausman, J., Hall, B.H., Griliches, Z., 1984. Econometric models for count data with an application to the patents R&D relationship. Econometrica 52 (4), 909–938. https://doi.org/10.2307/1911191.
Hicks, J.R., 1932. The Theory of Wages. MacMillan, London.
IEA, 2018. Energy Technology Perspectives 2017. . Retrieved from 〈https://www.iea.org/etp/〉.
Jaffe, A.A.B., Palmer, K., 1997. Environmental regulation and innovation: a panel data study. Rev. Econ. Stat. 79 (4), 610–619. https://doi.org/10.1162/003465397557196.
Jaffe, A.B., Newell, R.G., Stavins, R.N., 2003. Technological change and the environment. Handbook of Environmental Economics 1. pp. 462–516.
Jaffe, Newell, R., Stavins, R., 2002. Environmental policy and technological change. In: Environmental and Resource Economics. 22. Kluwer Academic Publishers, pp. 41–69 Retrieved from 〈http://link.springer.com/article/10.1023/A:1015519401088〉.
Johnstone, N., Haščič, I., Popp, D., 2010. Renewable energy policies and technological innovation: Evidence based on patent counts. Environ. Resour. Econ. 45 (1), 133–155. https://doi.org/10.1007/s10640-009-9309-1.
Lanjouw, J.O., Mody, A., Bank, W., 1996. Innovation and the international diffusion of environmentally responsive technology. Res. Policy 25 (4), 549–571. https://doi.org/10.1016/0048-7333(95)00853-5.
Ledbetter, L., Sandahl, T., Gilbride, M., Calwell, C., Steward, H., 2013. Compact fluorescent lighting in America: lessons learned on the way to market. J. Chem. Inf. Model. 53 (9), 1689–1699. https://doi.org/10.1017/CBO9781107415324.004.
Lim, S.-R., Kang, D., Ogunseitan, O.A., Schoenung, J.M., 2013. Potential environmental impacts from the metals in incandescent, compact fluorescent lamp (CFL), and light-emitting diode (LED) bulbs. Environ. Sci. Technol. 47 (2), 1040–1047. https://doi.org/10.1021/es302886m.
Mowery, D., Rosenberg, N., 1979. The influence of market demand upon innovation: a critical review of some recent empirical studies. Res. Policy 8 (2), 102–153. https://doi.org/10.1016/0048-7333(79)90019-2.
National Research Council, 2005. Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look Forward.
Navigant Consulting, 2006. Solid-State Lighting Development Portfolio Solid-State Lighting Research and Development Portfolio. Multi-Year Program Plan FY'07-FY'12.
Navigant Consulting, 2014. Energy Savings Forecast of Solid-State Lighting in General Illumination Applications. U.S. Department of Energy Report.
Nemet, G.F., 2009. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. Res. Policy 38 (5), 700–709. https://doi.org/10.1016/j.respol.2009.01.004.
Newell, R., Jaffe, A.B., Stavins, R.N., 1999. The induced innovation hypothesis and energy-saving technological change. Q. J. Econ.. 〈http://qje.oxfordjournals.org/content/114/3/941.short〉.
Noailly, J., 2012. Improving the energy efficiency of buildings: the impact of environmental policy on technological innovation. Energy Econ. 34 (3), 795–806. https://doi.org/10.1016/j.eneco.2011.07.015.
Noailly, J., Ryfisch, D., 2015. Multinational firms and the internationalization of green R &D: a review of the evidence and policy implications. Energy Policy. https://doi.org/10.1016/j.enpol.2015.03.002.
Organisation for Economic Co-operation and Development (OECD), 2012. Energy and Climate Policy: Bending the Technological Trajectory. https://doi.org/10.1787/9789264174573-en.
Peters, M., Schneider, M., Griesshaber, T., Hoffmann, V.H., 2012. The impact of technology-push and demand-pull policies on technical change – Does the locus of policies matter? Res. Policy 41 (8), 1296–1308. https://doi.org/10.1016/j.respol.2012.02.004.
Popp, D., 2002. Induced Innovation and energy prices. Am. Econ. Rev. 92 (1), 160–180.
Popp, D., 2005. Lessons from patents: using patents to measure technological change in environmental models. Ecol. Econ. 54 (2–3), 209–226. https://doi.org/10.1016/j.ecolecon.2005.01.001.
Popp, D., 2006. International innovation and diffusion of air pollution control technologies: the effects of NOX and SO2 regulation in the US, Japan, and Germany. J. Environ. Econ. Manag. 51 (1), 46–71. https://doi.org/10.1016/j.jeem.2005.04.006.
Popp, D., Hafner, T., Johnstone, N., 2011. Environmental policy vs. public pressure: innovation and diffusion of alternative bleaching technologies in the pulp industry. Res. Policy 40 (9), 1253–1268. https://doi.org/10.1016/j.respol.2011.05.018.
Popp, D., Newell, R.G., Jaffe, A.B., 2010. Chapter 21 - Energy, the Environment, and Technological Change. In: Hall, B.H., N.B.T.-H. of the E. of I. Rosenberg (Eds.), Handbook of the Economics of Innovation 2. North-Holland, pp. 873–937. https://doi.org/10.1016/S0169-7218(10)02005-8. (Volume 2).
Rennings, K., 2000. Redefining innovation - Eco-innovation research and the contribution from ecological economics. Ecol. Econ. 32 (2), 319–332. https://doi.org/10.1016/S0921-8009(99)00112-3.
Sanderson, S.W., Simons, K.L., 2014. Light emitting diodes and the lighting revolution: the Emergence of a solid-state lighting industry. Res. Policy 43 (10), 1730–1746. https://doi.org/10.1016/j.respol.2014.07.011.
Scherer, F.M., 1965. Firm size, market structure, opportunity, and the output of Patented inventions. Am. Econ. Rev. 55 (5), 1097–1125.
Schmookler, J., 1962. Economic sources of inventive activity. J. Econ. Hist. 22 (01), 1–20. https://doi.org/10.1017/S0022050700102311.
Schmookler, J., 1966. Invention and Economic Growth 26 Harvard University Press Cambridge, MA.
Simons, K.L., Sanderson, S.W., 2011. Global technology development in solid state lighting. Int. J. High. Speed Electron. Syst. 20 (359). 〈http://www.worldscientific.com/doi/abs/10.1142/S0129156411006647#.VtuBFG-ydMk.mendeley〉.
Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., Schellnhuber, H.J., 2018. Trajectories of the earth system in the anthropocene. Proc. Natl. Acad. Sci. USA 115 (33), 8252–8259. https://doi.org/10.1073/PNAS.1810141115.
Verdolini, E., Galeotti, M., 2011. At home and abroad: an empirical analysis of innovation and diffusion in energy technologies. J. Environ. Econ. Manag. 61 (2), 119–134. https://doi.org/10.1016/j.jeem.2010.08.004.
Vollebergh, H.R.J., van der Werf, E., 2014. The role of standards in eco-innovation: lessons for policymakers. Rev. Environ. Econ. Policy 8 (2), 230–248. https://doi.org/10.1093/reep/reu004.
Zhu, D., Humphreys, C.J., 2012. Lighting. In: Ginley, David S., Cahen, David (Eds.), Fundamentals of Materials for Energy and EnvironmentalSustainability. Cambridge University Press (Chapter 35).