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PUBLIC GREEN DEMAND AND GREEN INNOVATION: EVIDENCE FROM US FIRMS

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Public Green Demand and Green Innovation: Evidence from US Firms

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Abstract

Achieving net-zero emissions alongside sustained economic growth necessitates unprecedented innovation efforts. Demand serves as a pivotal driver in this endeavor. This paper presents novel evidence concerning the relationship between public procurement for green products and services (GPP) and firm innovation. GPP widens market niches for new green goods and accelerates the adaptation of conventional goods to meet more rigorous environmental standards. This, in turn, fosters the creative response of the firm, stimulating innovation in both new green products and new green processes. The empirical analysis focuses on US publicly listed innovative companies from 2004 to 2016. The results demonstrate that increases in GPP stimulate green innovation overall, particularly process-related. Moreover, we observe that this is more pronounced in large and incumbent firms, as well as in firms with substantial knowledge and organizational capital. These results provide valuable insights for designing effective policy frameworks to expedite the green transition while ensuring continued economic growth.

Keywords: public procurement; green innovation; process innovation; green process innovation; green transition

JEL codes: O33, H57, Q55, Q58

1 Introduction

The transition towards a zero-carbon economy is one of the most challenging economic transformations in history. A profound restructuring across all sectors of the economy is required, ranging from energy production and transportation to housing, agriculture, manufacturing, and even service industries. This imperative arises from the need to curtail climate change and mitigate environmental degradation effectively. Over the next decades, these efforts are inescapable for societies to successfully limit the consequences of climate change and secure a sustainable future for generations to come.

Pursuing this massive transformation while maintaining sustained economic growth is a daunting challenge. Indeed, in past economic and industrial revolutions, carbon emissions have been considered an incidental and cost-free consequence of progress. In the green transition, there is a shift towards internalizing these emissions. This involves government subsidies, investments in new infrastructures, and the implementation of carbon pricing mechanisms for both businesses and consumers, requiring the reevaluation of the actual costs of burning fossil fuels. Consistent investments in innovation are deemed crucial to converting these costs into opportunities. These investments should embrace all firm operations, from organizational structures to production processes, as well as the marketing and distribution of final products and services throughout their life cycles. Therefore, obtaining an in-depth understanding of the mechanisms through which green innovation can be sustained is of primary importance.

Among the drivers of green innovation, both demand- and supply-side tools have been identified as important (Crespi et al., 2015; Barbieri et al., 2016). While, on the supply side, the range of policy instruments available – and implemented – has been extensively studied and explored, the demand side of eco-innovation drivers has remained relatively underexplored, surprisingly. In fact, firms seize opportunities as they arise, often driven by changes in market demand. This makes demand a key driver of technical and technological progress (Kaldor, 1966; Schmookler, 1966; Antonelli and Gehringer, 2015, 2019).

When dealing with green demand, relying solely on market forces to restore efficiency comes with risks. Indeed, it's crucial to acknowledge that consumer preferences evolve gradually, develop endogenously as a function of consumers' life histories, and are highly persistent once formed (Bronnenberg et al., 2012). Consequently, demand shifts driven by changes in consumers' preferences might be slow; this impacts the speed of the process for changing production routines and the generation and introduction of new technologies by firms. Yet, the urgency of combating global warming demands the activation of a rapid innovative response by the firm. Thus, there is an urgent need to accelerate the creation and growth of green demand exogenously, thereby triggering a positive cycle of green innovation investments. Public spending emerges as a vital instrument in catalyzing and expediting this process, facilitating interventions that can drive the transition towards sustainability at a pace aligned with the challenges posed by climate change.

Gaining insights into the micro-level mechanisms that connect green demand with green innovation is pivotal for designing effective policy frameworks aimed at accelerating the transition to a sustainable economy while ensuring economic growth. This paper contributes to this literature by investigating the relationship between green public procurement (henceforth GPP) as a proactive environmental demand-side policy tool – i.e., the purchase of products and services with superior environmentally-friendly characteristics and lower energy consumption or carbon footprint than conventional ones – and firm innovation in new green technologies and processes.

GPP is a lever to widen niches for new green products and services, and a lever for faster adaptation of the production of conventional products and services to meet more rigorous environmental standards. Hence, we argue that GPP triggers heterogeneous innovative responses from the firm. First, when GPP creates a sufficiently high demand for relatively new green goods, firms better positioned to seize this opportunity respond creatively, leveraging green product innovation. Second, when GPP involves conventional products and services that must comply with stricter environmental standards, firms primarily adapt their production leveraging process innovation to accommodate efficiently green-oriented demand shifts. Both responses warrant attention: while the former inherently enhances product variety and business dynamism, the latter is necessary for adapting more rapidly production processes to stricter environmental standards while maintaining operational efficiency. Hence, both are necessary for expediting the transition without compromising economic growth.

We conduct the analysis on US publicly listed innovative companies over the period 2004-2016. We measure green public demand at the MSA-sector level exploiting data on federal procurement expenditures, and firm innovation through patenting activity. Our findings reveal that firms respond to increases in MSA-sector public green demand by innovating in green technologies, significantly shifting their innovation trajectories. Notably, we observe heightened innovation intensity in green technologies compared to other technologies as a result of GPP increases. Moreover, we estimate high rates of process-related green innovation as a response to GPP increases. This result suggests that firms largely leverage process innovation to adapt efficiently their production to public demand shifts towards more sustainable goods. Lastly, our analysis uncovers intriguing heterogeneity, with larger effects observed in large and more established firms, and in firms characterized by high levels of knowledge and organizational capital intensities; this is particularly evident when green process innovation is considered.

This work contributes to the growing body of literature investigating the role of public demand in fostering the development of green technologies. While numerous studies address the design of GPP and the barriers to its diffusion, the empirical evidence on its impact on eco-innovation is underdeveloped. This is partly due to the very place-specific nature of public procurement initiatives, which vary both within and between regions over time. We explicitly take into consideration the role of the *local* public demand for green(er) goods and services and how this influences the level of innovative activities carried out by firms in a given local area, showing that the former induces a creative response by firms. These findings corroborate the argument about the potential for local administrative bodies in the support and diffusion of GTs (Ghisetti and Quatraro, 2017; Lauer and Liefner, 2019; Orsatti et al., 2020; Nesterova et al., 2020; Tchórzewska et al., 2022).

The paper proceeds as follows. Section 2 discusses the theoretical background. Section 3 describes data, variables and empirical methods. Section 4 presents and discusses the results. Section 5 concludes.

2 Background

Eco-innovations possess distinct characteristics that differentiate them from other forms of innovation (Rennings, 2000; Fusillo, 2023). Notably, in addition to the conventional sources of externalities affecting all types of knowledge, green knowledge also yields positive effects on firm-level as well as local-level environmental performance. The resulting market failure and the challenge of internalizing external effects often lead to sub-optimal investments in green technologies (GTs). Therefore, policy intervention becomes essential to keep investments in green innovation on a sustained path. Accordingly, the fundamental premise of Porter's hypothesis regarding environmental performances and competitiveness revolves around the positive influence of environmental regulations on innovation (Porter and van der Linde, 1995; Bitat, 2018).

Environmental policy encompasses a broad spectrum of instruments that may be classified into supply-side and demand-side approaches. While the former aims to foster the advancement of technological expertise in environmentally friendly sectors through targeted research and development (R&D) initiatives (Costantini et al., 2015; Orsatti, 2023), the latter includes a range of strategies, from establishing technological standards and regulating prices to setting pollution thresholds. Demand-side policies typically seek to stimulate innovation by enlarging market size and reducing uncertainties related to demand, thereby fostering both the development and dissemination of innovative products and services (Caravella and Crespi, 2021). In the context of environmental innovation, these policies are specifically designed to incentivize companies to enhance their production processes, thereby improving environmental performance (Orsatti et al., 2020). According to such inducement mechanism, as the regulatory framework becomes more stringent, firms are increasingly incentivized to implement organizational and technological innovations to meet compliance requirements (Demirel and Kesidou, 2011). Consequently, the rise in demand from downstream firms for green technologies is anticipated to foster the development of new markets or expand existing ones. This creates economic incentives for upstream green technology suppliers to invest resources in green R&D (Costantini et al., 2015).

Within this context, public procurement (PP) is the primary operational tool for demand-side policies. Within the OECD area, PP accounts for nearly 30% of national government expenditures and represents over 12% of GDP.[1] By consolidating and creating markets, thereby reducing uncertainty, PP offers suppliers strong incentives to develop innovative solutions that facilitate the improvement of goods and services. Consequently, PP is acknowledged as a pivotal force driving technological advancement (Uyarra and Flanagan, 2010), whether procurement explicitly aims to stimulate innovation (innovation-inducing) or not (regular). PP is indeed central to demand-side innovation policies (Dalpé et al., 1992; Edler and Georghiou, 2007; Edquist and Zabala-Iturriagagoitia, 2020).

PP has primarily been examined within the economics of innovation literature, where public spending on R&D has been shown to have a positive impact at the collective level by generating public knowledge that spills over, benefiting various actors within the innovation

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[1] https://www.oecd.org/gov/public-procurement/

system. Additionally, positive effects are associated with stimulating private firms' R&D expenditures (Wallsten, 2000).

Previous innovation literature also shows explicitly the positive impact of obtaining innovative public procurement awards on firms' innovation activities (Guerzoni and Raiteri, 2015; Caravella and Crespi, 2020; Czarnitzki et al., 2020; Stojčić et al., 2020). However, the role of public procurement in fostering the development of green technologies has only been recently addressed in the academic literature. Yet, green public procurement currently has a high political priority, as it is evident from the ongoing debates regarding its compulsory implementation within the European Union's public procurement framework (Pouikli, 2021), from the 2021 Sustainable Public Procurement Implementation Guidelines published by the UN Environment Programme (UNEP, 2021), and from the 2021 US Federal Sustainability Plan.[2]

GPP consists of integrating environmental standards into procurement processes to minimize the ecological footprint of public acquisitions, particularly in sectors like transportation, construction, and furnishing, known for their significant environmental impact. By incorporating sustainability criteria into public procurement, governments can strategically act as role models (Nykamp, 2020). GPP is essential for encouraging the adoption of environmentally friendly products and services by public authorities. It plays a crucial role in achieving environmental policy goals such as addressing climate change, preserving biodiversity, promoting resource efficiency, and fostering sustainable production and consumption. GPP initiatives effectively counteract environmental problems such as deforestation by sourcing wood products from sustainable forests and reduce greenhouse gas emissions by choosing low-carbon footprint products. Moreover, GPP contributes to waste reduction through waste-minimizing processes and packaging, encourages reuse and recycling, and aids in controlling air, water, and soil pollution by regulating hazardous substances (Pouikli, 2021).

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[2] Available at https://www.sustainability.gov/pdfs/federal-sustainability-plan.pdf.

Despite the high political priority that GPP has gained and the growing literature assessing the design of GPP initiatives and the barriers to its diffusion (Hall et al., 2016; Rainville, 2017; Edquist and Zabala-Iturriagagoitia, 2020; Rosell, 2021), empirical studies on its impact on eco-innovation are surprisingly lacking. Extant evidence mainly deals with case studies focused on specific classes of environmental criteria and primarily targeted at the effect on environmental outputs or economic performance, not environmental innovation (Cheng et al., 2018). Heterogeneous efforts and, consequently, hardly comparable findings with respect to the role of GPP, can be ascribed to the very place-specific nature of public procurement, which, in fact, exhibits variance both between and within regions over time (Heald and Short, 2002; Morgenroth, 2010). This places the institutional context at the forefront of the analysis of the drivers of green innovation (Hitaj, 2013; Nesta et al., 2014). As institutions are inherently tied to specific locations, empirical studies conducted at the micro, meso, and macro levels often regard the regional or national regulatory framework as a crucial factor in explaining variations in the capacity to foster eco-innovations among firms, regions, and countries (Barbieri et al., 2016).

A set of studies shows that regional administrative bodies have great potential to support diffusion processes using GPP, for instance, by nurturing early market formation and early adoptions (Ghisetti and Quatraro, 2017; Lauer and Liefner, 2019; Nesterova et al., 2020). Similarly, Orsatti et al. (2020) unveils the positive role of GPP for the generation of GTs at the local level in the US economy, providing robust estimates of a positive relationship between increases in GPP and increases in the number of green patents across US commuting zones, thus supporting the argument that the government expenditure lever can be effective in the promotion of the technology-driven sustainability transition.

Following this stream of studies, we contend that local public demand for green(er) products and services represents a crucial lever to foster firms' investments in new green technologies and improvement of existing goods and services. From this standpoint, place-specific GPP can be considered a direct form of public intervention to stimulate the demand for eco-innovation by the government (Parikka-Alhola, 2008).

One significant aspect of GPP is its potential to catalyze the introduction and proliferation of new green products and services. When government agencies commit to sourcing sustainable alternatives through their procurement processes, they create a substantial demand signal in the market. This demand serves as a powerful incentive for businesses to innovate and develop innovative solutions that align with environmental objectives. However, while the promotion of new green products is a desirable outcome of GPP, it is often accompanied by a more prevalent pattern of influencing traditional products to meet higher environmental standards. This phenomenon arises from the practical challenges associated with transitioning entire markets to entirely new technologies or practices overnight. As a result, GPP frequently acts as a catalyst for the rapid adaptation of conventional products and services to align with evolving sustainability requirements.

This dual role of GPP, as both a lever to enlarge niches for new green goods and an accelerator for the greening of existing offerings, underscores its versatility and prompts two complementary innovation responses from firms operating within the market. Firstly, when GPP generates substantial demand for emerging goods and services that align with green principles, companies well-positioned to seize this opportunity often respond by introducing novel product-driven green innovations. This response mechanism is akin to a ripple effect, wherein heightened demand for eco-friendly offerings incentivizes firms to invest in research and development, leading to the creation of innovative solutions that cater to evolving consumer preferences and market demands. Secondly, when GPP objectives primarily target conventional products and services that now must conform to heightened environmental standards, companies are compelled to adapt their production processes accordingly. This adaptation involves implementing new manufacturing techniques and technologies to efficiently incorporate environmentally friendly practices into their operations. Such changes are vital for maintaining competitiveness in a market increasingly shaped by environmental concerns and regulatory pressures. Both of these responses warrant careful consideration. The first, driven by increased demand for new green products and services, fosters product diversity and enhances competitiveness within the market. The second, triggered by the need to adapt conventional products and services to stricter environmental standards, ensures a smooth transition towards sustainability while safeguarding operational efficiency. It is worth to recognize that both avenues of innovation are indispensable for expediting the green transition without compromising economic growth.

The mechanisms through which public demand for green products and services is likely to foster the above-described dynamics across firms align with those described in the literature on eco-innovation (Orsatti et al., 2020). Accordingly, public policies can create the conditions for environmentally friendly innovation via two channels (Rennings, 2000). The first one consists of indirectly stimulating the derived demand for GTs on the part of polluting firms that are prepared to comply with stricter environmental regulation, while the second one is about directly supporting demand via procurement contracts (Johnstone et al., 2012). In both cases, the final result is the creation of new market niches or the expansion of existing markets for GTs (Nemet, 2009; Hoppmann et al., 2013).

3 Data and methods

In the empirical analysis, we investigate the relationship between increases in GPP and firm green innovation. The following subsection is dedicated to the description of the sample and the data sources. Subsection 3.2 describes the econometric models and the variables used.

3.1 Sample and data sources

Sample and financial data We conduct the empirical analysis on US publicly listed companies over the period 2004-2016. Firm-level financial information are from Compustat North America database. We restrict the sample to US firms conducting business in US dollars, with at least two years of observations for the main financial items, and with at least one patent filed at the United States Patent and Trademark Office (USPTO) during the period considered. We remove firms operating in the following sectors: utility (SIC Codes 4900-4999), financial (SIC Codes 6000-6999), and public services, international affairs or non-operating establishments (SIC Codes 9900+). We also remove firms reporting negative values for assets, employees, sales, and capital stock. Data on knowledge capital and organization capital are from Ewens et al. (2019).[3] We deflate all monetary items using the BEA 2017 GDP deflator. Our final sample consists of a maximum of 1,705 firms and 14,369 firm-year observations.

Public procurement data Data on public procurement are from USAspending, the official open data source of US federal spending information, including information on federal awards such as contracts, grants, and loans.[4] We collect all federal contracts from the fiscal year 2003 to fiscal year 2015. Contract-level information used in this paper includes the amount (in current dollars) and date of executed payments, the location of execution (at the 5-digits ZIP code level), the NAICS code reported (for industry allocation), and the type of prevalent product or service procured. These information allow us to geolocalize each payment and assign to it a unique date, a specific industrial sector, and the product or service prevalence. Products or services are classified according to the Product and Service Codes Manual (PSC, August 2015 Edition). We follow Orsatti et al. (2020) and use the PSC Manual to retrieve information on environmental attributes associated with procured

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[3] Data accessible at https://github.com/michaelewens/Intangible-capital-stocks

[4] Data accessible at https://www.usaspending.gov.

contracts and, through these attributes, identify procured 'green' contracts.[5] Combining these information, we reconstruct a sector-MSA public procurement time-series (PP) for the period 2003-2016, differentiating between green and non-green procurement (GPP and BPP, respectively). PP, GPP, and BPP monetary amounts are deflated using the BEA 2017 GDP deflator. We link sector-MSA public procurement expenditures to US-listed firms based on the firm-level combination of headquarter address and NAICS code of activity.

Patent data We proxy firm innovation activity with patent data. Relying on the work by Arora et al. (2021), we link patents filed at the USPTO to US-listed companies.[6] Information on patent characteristics (e.g., filing year, technology classification, etc.) are from PatentsView.[7] To identify green patents, we follow recent literature and exploit the Y-tagging scheme of the Cooperative Patent Classification (CPC) at the 4-digits level. Green patents are patents classified in the CPC range Y02A-Y04S.[8] To identify patents that relate to the introduction of a new or improved process (i.e. process patents), we rely on the Process Innovation Patent Dataset developed by Bena and Simintzi (2023).[9] Bena and Simintzi (2023) identify process patents employing textual analysis instruments on patent claims.[10] The database contains the number of claims and the number of process claims for all patents

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[5] Environmental attributes refer to 'Energy efficient', 'Biobased' or 'Environmentally preferable'.

[6] The Duke Innovation & SCientific Enterprises Research Network (DISCERN) database is accessible at https://zenodo.org/records/4320782.

[7] Data accessible at https://patentsview.org/.

[8] The Y-tagging scheme for green technologies includes both climate change adaptation and climate change mitigation technologies. The last domain is further divided into 7 subclasses: Climate change mitigation technologies related to buildings; Capture, storage, sequestration or disposal of greenhouse gases; Climate change mitigation technologies in ICT; Reduction of greenhouse gas emissions, related to energy generation, transmission or distribution; Climate change mitigation technologies in the production or processing of goods; Climate change mitigation technologies related to transportation; Climate change mitigation technologies related to wastewater treatment or waste management

[9] Data accessible at https://www.janbena.com/en/process-innovation-patent-dataset.

[10] As the authors stress, in complying with Section 101 of the USPTO Patent Statute, patentable inventions may belong to four categories, among which it is listed the invention of a new process. The type of invention is normally explicitly and directly reported in the patent claim preamble, i.e., the first textual section of claims. Thus, they exploit information in patent claim preambles to distinguish between process claims and other types of claims.

granted by the USPTO between 1976 and June 2021. For the purposes of our analysis, we adopt a conservative approach and consider process patents as those patents in which all listed claims have been identified as process-related.

3.2 Model and Variables

We fit models of the following form to investigate the relationship between green public procurement and firm green innovation:

$$Y_{i,m,s,t} = \theta_i + \lambda_t + \beta_1 GPP_{m,s,t-1} + \Gamma \boldsymbol{X}'_{i,t-1} + \Pi \boldsymbol{M}'_{m,t-1} + \Phi \boldsymbol{S}'_{s,t-1} + \epsilon_{i,t} \tag{1}$$

where i, m, s, and t index, respectively, firm, MSA, 3-digits NAICS and year. $Y_{i,m,s,t}$ is, alternatively: (i) the log-transformed number (augmented by 1) of green patents; (ii) the number of green patents scaled by total patents (*green patent share*); (iii) the number of green patents scaled by the number of non-green patents (*green patent intensity*); (iv) the log-transformed number (augmented by 1) of green process patents; (v) the number of green process patents over total green patents (*green process patent share*); (vi) the number of green process patents over green non-process patents (*green process patent intensity*). θ_i and λ_t are, respectively, firm and year fixed effects.[11] $GPP_{m,s,t-1}$ is the log-transformed amount (in 2017 USD, augmented by 1) of green public procurement expenditures, measured at the MSA-sector (3-digits NAICS) level, lagged one year.[12] $\boldsymbol{X}'_{i,t-1}$ is a vector of firm-level time-varying control variables, lagged one year, that account for firm characteristics that prior research has identified as influential factors in innovation. First, we include knowledge capital

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[11] In more demanding specifications, we include, alternatively, a series of specific fixed effects such as $MSA \times year$, $Sector(NAICS3) \times year$, $State \times year$ together with $Sector(NAICS2) \times year$ to check the robustness of the main results. The results of these robustness tests, reported in Table 6, fully confirm our main findings.

[12] In additional estimations presented in Section 4.2, we differentiate public procurement between expenditures for green products and for green services and exploit product-related public demand and service-related public demand as explanatory variables, independently. Results of these estimations are reported in Table 6.

scaled by total assets ($KnowCap/Assets$) and organization capital scaled by total assets ($OrgCap/Assets$) to control for cumulative innovation effort and organization capital stock.[13] Larger and more capital-intensive firms tend to produce more patents (Hall and Ziedonis, 2001). Consequently, we introduce the natural logarithm of total assets ($Ln(Assets)$) to control for company size, with alternative measures like net sales or employee count yielding consistent results. Additionally, we incorporate the logarithm of net Property, Plant, and Equipment (PPE) scaled by total assets ($Ln(PPE/Assets)$) to address capital intensity. The logarithm of net sales scaled by the number of employees ($Ln(Sales/Emp)$) serves as a proxy for labor productivity and quality, reflecting the potential link between labor efficiency and innovation productivity. We also include return on assets (ROA) to capture operational profitability. Furthermore, we include a proxy for growth opportunities like the market-to-book ratio (M/B). The cash-to-assets ratio ($Cash/Assets$) and leverage ratio ($Leverage$) are introduced to control for the impact of cash holdings and capital structure on innovation. Lastly, to account for the influence of a company's life cycle on its innovation capacity, we incorporate the natural logarithm of firm age, $Ln(FirmAge)$, which represents the years since the company's entry into the Compustat database. $\boldsymbol{M}'_{m,t-1}$ is a vector of MSA-level time-varying control variables, lagged one year, that might simultaneously influence both firm innovation and local PP. These variables are the log-transformed number of patents granted to listed firms headquartered in MSA m ($MSAPAT$, focal firm's patents excluded) and the natural logarithm of GDP ($MSAGDP$). $\boldsymbol{S}'_{s,t-1}$ is a vector of 3-digits NAICS-level time-varying control variables, lagged one year, that control for sectoral dynamics that might explain both firm patenting and public decisions in allocating federal contracts. These control

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[13] Data on firm-level knowledge and organization capital are from Ewens et al. (2019). Ewens et al. (2019) analyze market data from acquisitions, liquidations, and bankruptcies to determine the values of identifiable intangible assets and goodwill. By comparing these values with the firm's historical spending on R&D and SG&A, they estimate parameters for the depreciation rate of R&D investment and the portion of SG&A allocated to organizational capital. They use these parameters to construct accurate measures of knowledge and organizational capital for the universe of Compustat firms for the period 1978-2017.

variables are the log-transformed number of patents filed by listed companies operating in sector s and headquartered in MSAs different than m ($NAICSPAT$), and the level of sales concentration of the sector ($Herfindahl$). $\epsilon_{i,t}$ is the error term. We estimate the model with OLS panel fixed effects estimators. Observations are weighted by the number of firm patents, averaged over the sample period, though we obtain similar results when observations are weighted by firm sales or by firm R&D (Autor et al., 2020). We cluster standard errors at the firm level.

4 Results

4.1 GPP and green innovation

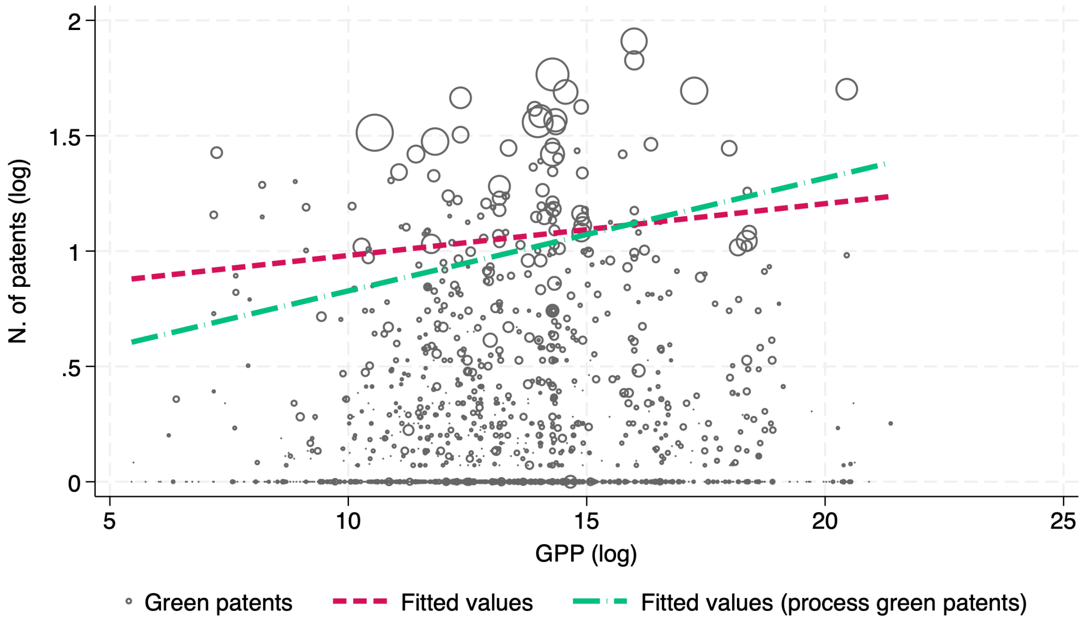
Table 1 reports the descriptive statistics of the variables used in the analysis. We start our exploration of the relationship between GPP and green innovation with Figure 1, in which we show the cross-sectional relationship between the average level of federal expenditures in green products and services measured at the metropolitan-sector level (x-axis) and the firm-level average number of annual patents in green technologies (y-axis) over the period 2003-2016. The figure shows a positive relationship: to higher sector-area levels of GPP are associated higher firm-level rates of patenting in green technologies (as also signaled by the positive shape of the red dashed line that refers to the fitted values of this cross sectional relationship). Interestingly, we observe an even more positive relationship when considering the average number of green process patents (green dashed dot steeper line in the figure). This exploratory analysis suggests two insights. First, firms headquartered in metropolitan areas and operating in sectors with higher levels of federal green procurement generate on average more green patents. Second, this simple statistical positive association is even stronger when considering green process patents, suggesting that GPP can activate innovation activities that are required to adapt production process to meet more rigorous environmental standards. We investigate these mechanisms more rigorously in the next steps of the analysis by means of regression methods.

Table 1: Descriptive statistics

	mean	median	sd
Firm level variables			
Total patents	29.584	2.000	137.716
Green patents	1.881	0.000	13.674
Total process patents	4.691	0.000	22.557
Green process patents	0.398	0.000	3.335
N. of employees (Emp, in 1,000)	7.428	0.630	25.029
Assets (in million)	4396.881	290.851	20200.956
PPE/Assets	0.401	0.295	0.408
KnowCap/Assets	0.644	0.171	3.734
OrgCap/Assets	0.716	0.264	3.707
Sales/Emp (in $1,000)	388.018	279.582	1165.238
ROA	-0.284	0.088	3.015
M/B	4.347	2.050	24.131
Cash/Assets	0.219	0.149	0.212
Leverage	0.486	0.113	7.401
Firm age (in years)	22.803	18.000	15.767
MSA-NAICS level variables			
Public procurement (total, in million)	582.964	88.254	2682.749
Public procurement (green, in million)	20.106	0.249	138.966
NAICS level variables			
Herfindahl	0.140	0.001	0.309
NAICS PAT	6800.131	4531.000	7363.939
MSA level variables			
MSA GDP	1868.115	443.174	3202.792
MSA PAT	2053.959	1035.000	3043.744
Observations	14369		

Table 2 reports our first set of regression results obtained according to Equation 1. In columns I-IV, the dependent variable is the natural logarithm of the number of green patents, augmented by 1. Column I considers the total amount of public procurement (PP)

Figure 1: Cross sectional relationship between GPP and green patenting



measured at the MSA-sector level as main explanatory variable, while columns II and III refer to, alternatively, non-green public procurement (BPP in column II) and green public procurement (GPP in column III). In column IV we include both green and non-green public procurement together. We estimate a non-significant coefficient for overall public procurement expenditures (column I), as well as non-green public procurement (columns II and IV). Conversely, we estimate a positive and statistically significant coefficient for GPP, both when estimated in isolation (column III) and when BPP is controlled for (column IV). Precisely, we estimate that a 1% increase in GPP is associated with a 2.8% increase in the number of green patents. This result suggests that green public procurement as a proactive demand-oriented policy tool stimulates the innovative response from the firm, leading to higher rates of green innovation. In columns V and VI of Table 2, we take a step forward in the understanding of the relationship between GPP and green innovation. In column V, we look at the firm-level share of green patents as the outcome of interest (i.e., the number of green patents over total patents), while in column VI, we look at the intensity of green patents (i.e., the number of green patents over the number of non-green patents). We estimate a positive and statically significant coefficient for GPP in both cases (point estimate .003), suggesting that rising public demand for green products and services increases the relative weight and incidence of green innovation. In other words, firms respond by shifting their innovative effort and recomposing their technological portfolio towards more green innovation. In both columns V and VI, the non-significant role of non-green public procurement expenditures is confirmed.

For what concerns the control variables, we estimate a positive and significant coefficient for total assets and age across all specifications, confirming that larger and more experienced firms are more likely to invest resources in the generation of GTs. We also find a positive and significant coefficient for the variables $MSAPAT$ when focusing on the share of green patents (column V). Lastly, in columns I, II, and IV we estimate a negative and weakly significant coefficient for the $Ln(Sales/Emp)$ variable. We do not find significant coefficients related to the other control variables.

The evidence reported in Table 2 shows that increases in the level of GPP are positively associated with the rate of firm-level green patenting activity, and with its incidence and relative weight. When federal spending prioritizes the procurement of sustainable alternatives, it sends a significant demand signal to the market. This demand pulls firms to innovate and devise solutions that adhere to environmental goals.

We then turn our attention to the direction of the firm's response to changes in GPP. Precisely, we focus on green process patents. GPP frequently acts as a catalyst for the adaptation of conventional products and services to stricter sustainability requirements. We contend that this adaptation to be efficient requires primarily the introduction of new processes. Therefore, our expectation is to estimate a positive and significant relationship between increases in GPP and the rate of generation of green process patents. Table 3 reports

Table 2: Public procurement and green patents

	Total				Share	Intensity
	(I)	(II)	(III)	(IV)	(V)	(VI)
PP	0.039					
	(0.033)					
BPP		0.039		0.033	0.004	0.002
		(0.034)		(0.032)	(0.004)	(0.004)
GPP			0.028^{***}	0.028^{***}	0.003^{***}	0.003^{**}
			(0.008)	(0.008)	(0.001)	(0.001)
Ln(Assets)	0.274^{***}	0.274^{***}	0.282^{***}	0.281^{***}	0.030^{***}	0.024^{***}
	(0.089)	(0.089)	(0.085)	(0.085)	(0.009)	(0.008)
Ln(PPE/Assets)	0.106	0.105	0.094	0.095	-0.011	-0.010
	(0.313)	(0.313)	(0.310)	(0.310)	(0.038)	(0.037)
KnowCap/Assets	0.254	0.256	0.211	0.210	0.019	0.015
	(0.172)	(0.172)	(0.152)	(0.152)	(0.019)	(0.018)
OrgCap/Assets	0.024	0.024	0.021	0.021	0.002	0.001
	(0.021)	(0.021)	(0.020)	(0.020)	(0.002)	(0.002)
Ln(Sales/Emp)	-0.117^{*}	-0.117^{*}	-0.115	-0.116^{*}	-0.011	-0.012
	(0.070)	(0.070)	(0.070)	(0.069)	(0.008)	(0.008)
ROA	0.061	0.062	0.043	0.045	0.002	0.001
	(0.050)	(0.050)	(0.040)	(0.041)	(0.005)	(0.005)
M/B	0.003	0.003	0.003	0.003	0.000	0.000
	(0.004)	(0.004)	(0.004)	(0.003)	(0.001)	(0.001)
Cash/Assets	-0.340	-0.339	-0.378	-0.384	0.007	-0.002
	(0.348)	(0.348)	(0.332)	(0.329)	(0.046)	(0.047)
Leverage	-0.032	-0.032	-0.027	-0.027	-0.003	-0.002
	(0.020)	(0.020)	(0.018)	(0.019)	(0.002)	(0.002)
Ln(Firm age)	0.662^{***}	0.660^{***}	0.662^{***}	0.668^{***}	0.137^{***}	0.136^{***}
	(0.219)	(0.219)	(0.218)	(0.217)	(0.032)	(0.031)
Herfindahl	0.323	0.323	0.962	0.952	0.174	0.189
	(0.812)	(0.812)	(0.856)	(0.860)	(0.134)	(0.124)
MSA GDP	-0.215	-0.216	-0.149	-0.152	0.019	0.017
	(0.431)	(0.431)	(0.426)	(0.422)	(0.052)	(0.047)
MSA PAT	0.116	0.116	0.125	0.120	0.020^{*}	0.018
	(0.094)	(0.095)	(0.090)	(0.088)	(0.012)	(0.012)
NAICS PAT	0.085	0.083	0.118	0.124	0.014	0.015
	(0.154)	(0.154)	(0.146)	(0.146)	(0.023)	(0.021)
Firm FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Observations	14369	14369	14369	14369	14369	14369
Adj. R2	0.88	0.88	0.88	0.88	0.83	0.77

Dep var: firm log-transformed number (augmented by 1) of green patents in columns I-IV, green patents over total patents (green patent share) in column V, green patents over non-green patents (green patent intensity) in column VI. *PP*, *BPP*, and *GPP* are, respectively, the log-transformed amount (in 2017 USD, augmented by 1) of total, non-green, and green public procurement expenditures, measured at the MSA-sector (3-digits NAICS) level. All independent variables are lagged by one year. All models are estimated with fixed effects OLS estimators and weighted by the firm number of filed patents averaged over the sample period. Heteroskedastic-robust standard errors, reported in parentheses, are clustered at the firm level. *p<0.1; **p<0.05; ***p<0.01

the result of this examination.

In line with Table 2, columns I-IV of Table 3 estimate the relationship between changes in, respectively, local total public procurement (column I), non-green public procurement (column II), green public procurement (column III) and both green and non-green public procurement together (column IV), and changes in the firm's rate of generation of green process patents. We estimate a non-significant coefficient of both total public procurement (PP) and non-green public procurement (BPP) across all specifications. Conversely and as expected, we estimate a positive and statistically significant coefficient for green public procurement (GPP), both when considered independently (column III) and when included together with BPP (column IV). Precisely, we find that a 1% increase in GPP is associated with about 1.8% increase in green process patents. This result suggests that firms respond to increases in GPP leveraging process innovation to efficiently adapt production and comply with stricter environmental requirements led by public demand. In columns V and VI of Table 3, we estimate the full model by employing as a dependent variable, respectively, the share (i.e. green process patents over total green patents) and the intensity (i.e. green process patents over non-process green patents) of green process patents. We estimate a positive and significant coefficient of GPP in both cases (point estimates, respectively, .003 and .01), suggesting that firms respond to increases in GPP by rising the intensity of their process innovation activities. We interpret this result as evidence of a necessary adaptation of production processes to meet stricter environmental requirements from the final (public) demand for conventional products and services. This adaptation in production to be efficient requires new processes. Hence, firms respond leveraging green process innovation to efficiently meet the new demand standards.

Concerning the control variables, we estimate positive and significant coefficients for $knowCap$ (columns I-II) and firm age (columns V and VI). Conversely, we estimate negative coefficients for $MSAGDP$ and $leverage$ (columns I, II, and IV).

Table 3: Public procurement and green process patents

	Total				Share	Intensity
	(I)	(II)	(III)	(IV)	(V)	(VI)
PP	0.039					
	(0.041)					
BPP		0.034		0.030	0.007	0.004
		(0.042)		(0.041)	(0.010)	(0.020)
GPP			0.018***	0.017***	0.003*	0.010***
			(0.005)	(0.005)	(0.002)	(0.003)
Ln(Assets)	0.097	0.097	0.102	0.102	0.030	0.010
	(0.089)	(0.089)	(0.086)	(0.087)	(0.019)	(0.031)
Ln(PPE/Assets)	-0.509	-0.510	-0.517	-0.516	-0.077	-0.157
	(0.341)	(0.341)	(0.344)	(0.346)	(0.083)	(0.146)
KnowCap/Assets	0.254*	0.256*	0.228	0.228	0.051	0.080
	(0.153)	(0.155)	(0.141)	(0.141)	(0.032)	(0.049)
OrgCap/Assets	0.010	0.010	0.008	0.008	0.002	0.002
	(0.013)	(0.014)	(0.013)	(0.013)	(0.003)	(0.005)
Ln(Sales/Emp)	-0.027	-0.027	-0.026	-0.026	-0.002	-0.035
	(0.074)	(0.075)	(0.075)	(0.075)	(0.018)	(0.029)
ROA	0.026	0.026	0.014	0.016	0.001	0.009
	(0.035)	(0.035)	(0.032)	(0.031)	(0.009)	(0.014)
M/B	0.002	0.002	0.001	0.001	-0.000	0.001
	(0.003)	(0.003)	(0.002)	(0.002)	(0.001)	(0.001)
Cash/Assets	-0.188	-0.186	-0.209	-0.214	0.029	0.058
	(0.279)	(0.280)	(0.276)	(0.276)	(0.088)	(0.119)
Leverage	-0.027*	-0.027*	-0.024	-0.025*	-0.004	-0.008
	(0.016)	(0.016)	(0.015)	(0.015)	(0.004)	(0.006)
Ln(Firm age)	0.144	0.142	0.140	0.147	0.106**	0.248***
	(0.181)	(0.182)	(0.183)	(0.180)	(0.048)	(0.076)
Herfindahl	0.386	0.386	0.787	0.777	0.362**	0.303
	(0.518)	(0.517)	(0.616)	(0.612)	(0.167)	(0.206)
MSA GDP	-0.756*	-0.757*	-0.715*	-0.718*	-0.229***	-0.281**
	(0.411)	(0.411)	(0.412)	(0.407)	(0.076)	(0.124)
MSA PAT	0.028	0.029	0.036	0.031	0.008	0.023
	(0.066)	(0.067)	(0.070)	(0.065)	(0.019)	(0.032)
NAICS PAT	-0.098	-0.100	-0.080	-0.075	-0.035	0.008
	(0.114)	(0.115)	(0.116)	(0.113)	(0.031)	(0.055)
Firm FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Observations	14369	14369	14369	14369	14369	14369
Adj. R2	0.79	0.79	0.79	0.79	0.55	0.51

Dep var: firm log-transformed number (augmented by 1) of green process patents in columns I-IV, green process patents over total green patents (green process patent share) in column V, green process patents over green non-process patents (green process patent intensity) in column VI. *PP*, *BPP*, and *GPP* are, respectively, the log-transformed amount (in 2017 USD, augmented by 1) of total, non-green, and green public procurement expenditures, measured at the MSA-sector (3-digits NAICS) level. All independent variables are lagged by one year. All models are estimated with fixed effects OLS estimators and weighted by the firm number of filed patents averaged over the sample period. Heteroskedastic-robust standard errors, reported in parentheses, are clustered at the firm level. *p<0.1; **p<0.05; ***p<0.01

4.2 Heterogeneity and robustness tests

The evidence discussed so far supports the idea that GPP as a demand-side proactive public policy tool creates prospective opportunities that stimulate the innovative response of the firm, which intensively leverages process green innovation. However, the ability to seize the green demand opportunities and to react creatively may vary across firms. In order to further explore the role of local GPP in stimulating green innovations at the firm level and test firms' heterogeneity in their reaction, we examine our results by partitioning the sample according to four firm-level characteristics. We report the results of these additional estimations in Table 4. The regressions include all control variables and fixed effects as in Tables 2 and 3.[14]

First, large firms operate at large scale and across multiple products and markets. Hence, they might be better positioned than small firms to take advantage of the publicly-driven rise in the demand for green products and services. Moreover, size could also explain the direction of the green innovative response towards high rates of process innovation because of the cost-spreading advantage of size in benefiting from the improved efficiency of production processes. In a similar vein, incumbent firms might be better equipped than young firms to take advantage of publicly-driven demand shocks. Therefore, we expect that the positive association between GPP and the rate of generation of green patents in general, process-related in particular, is stronger in large and incumbent firms. We use the level of total employment to measure the size of the firm, and the age (in years) since the company's entry into the Compustat database to differentiate between old and young firms. In columns I-II of Table 4 we focus on firm size heterogeneity and we split firms into two groups based on their employment level. Large firms are those with a level of total employment in the top quartile of the sample industry-year employment distribution, while small firms those in the bottom quartile. Panel A reports the results when the dependent variable is the number of

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[14] In order to save space, Table 4 reports only the estimated coefficients of the main variables of interest (i.e., GPP and BPP). Full model results are available upon request.

green patents. Panel B refers to the number of green process patents, while Panel C to its share of total green patents. We estimate a positive and significant coefficient of GPP on green patents in the sample of large firms, while a non-significant coefficient in the sample of small firms. Similarly, when we focus on green process patents, we estimate a positive and significant coefficient of GPP in the sample of large firms, and a non-significant coefficient in the sample of small firms. This is confirmed also when we focus on the share of green process patents. Columns III and IV of Table 4 report the results of the sample split by firm age. Incumbent (old) firms are those in the top quartile of the sample industry-year age distribution, while we identify young firms as those in the bottom quartile. We estimate positive coefficients of GPP in the sample of old firms in all panels, while non-significant coefficients in the sample of small firms. For both partitions of firm size and age, we do not find significant coefficients of BPP, except in the sample of small firms in Panel B and in Panel C.

In addition to size and age, we also look at firm heterogeneity with respect to knowledge capital and organization capital. Accordingly, we first partition our sample according to the top (High) and bottom (Low) quartiles of firms' knowledge capital scaled by total assets. Results of the estimation on the two subsamples are presented in Table 4, columns V and VI. In Panel A, we find that GPP is positively and significantly associated with green patents only in firms with high knowledge capital, with no significant effect on firms with low levels of knowledge capital. The result holds when focusing on the association with green process patents (Panel B), but we find a non-significant coefficient for GPP on the share of green process patents (Panel C). Again, the public demand creation is positively associated with firm green innovation activities when the public procurement expenditures are directed toward products and services with environmental content, while the role of non-green local public demand is not statistically significant. Secondly, we split the sample into two groups according to firms' organization capital ($OrgCap/Assets$). The $High$ group consists of firms in the

Table 4: Firm Heterogeneity

	Firm characteristics							
	Size		Age		Know. Cap.		Org. Cap.	
	Small (I)	Large (II)	Young (III)	Old (IV)	Low (V)	High (VI)	Low (VII)	High (VIII)
	Panel A – Dep. var.: *ln(1 + GT patents)*							
BPP	-0.006	0.049	0.019	0.055	0.033	0.037	-0.009	0.038
	(0.060)	(0.037)	(0.040)	(0.036)	(0.034)	(0.034)	(0.018)	(0.032)
GPP	0.011	0.028***	-0.010	0.022**	0.002	0.028***	-0.001	0.029***
	(0.007)	(0.008)	(0.010)	(0.009)	(0.010)	(0.008)	(0.005)	(0.008)
	Panel B – Dep. var.: *ln(1 + GT process patents)*							
BPP	0.071*	0.032	0.008	0.010	-0.011	0.033	-0.024	0.029
	(0.043)	(0.043)	(0.023)	(0.040)	(0.010)	(0.042)	(0.016)	(0.038)
GPP	-0.002	0.020***	0.003	0.018**	0.005	0.017***	-0.009*	0.020***
	(0.004)	(0.006)	(0.005)	(0.007)	(0.004)	(0.005)	(0.005)	(0.005)
	Panel C – Dep. var.: *ln(1 + GT process patents)/ln(1 + GT patents)*							
BPP	0.031*	0.005	0.008	-0.003	-0.007	0.007	-0.001	0.004
	(0.016)	(0.011)	(0.016)	(0.010)	(0.007)	(0.011)	(0.008)	(0.009)
GPP	-0.002	0.003*	0.002	0.004*	0.001	0.003	-0.001	0.004*
	(0.002)	(0.002)	(0.003)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)
Control variables:								
Firm-level	✓	✓	✓	✓	✓	✓	✓	✓
Sector-level	✓	✓	✓	✓	✓	✓	✓	✓
MSA-level	✓	✓	✓	✓	✓	✓	✓	✓
Fixed effects:								
Firm FE	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓
Observations	3246	3587	3877	3062	2563	4320	2913	4264
Adj. R2 (Panel A)	0.76	0.89	0.65	0.91	0.65	0.88	0.94	0.89
Adj. R2 (Panel B)	0.63	0.78	0.52	0.81	0.76	0.78	0.80	0.78
Adj. R2 (Panel C)	0.53	0.54	0.38	0.59	0.69	0.54	0.49	0.55

Dep var: firm log-transformed number (augmented by 1) of green patents in Panel A, green process patents in Panel B, green process patents over total green patents in Panel C. BPP and GPP are, respectively, the log-transformed amount (in 2017 USD, augmented by 1) of non-green, and green public procurement expenditures, measured at the MSA-sector (3-digits NAICS) level. The subsamples partition firms in the top quartile and bottom quartile based on the sector-year sample distribution of: total employment (columns I-II); age (columns III-IV); knowledge capital over total assets (columns V-VI); organization capital over total assets (columns VII-VIII). Models include the full set of control variables used in Table 2 and in Table 3 (coefficients not reported). All independent variables are lagged by one year. All models are estimated with fixed effects OLS estimators and weighted by the firm number of filed patents averaged over the sample period. Heteroskedastic-robust standard errors, reported in parentheses, are clustered at the firm level. *p<0.1; **p<0.05; ***p<0.01

top quartile of organization capital, while in the *Low* group, firms in the bottom quartile are considered. The results, reported in columns VII-VIII of Table 4, suggest that firms with higher levels of organization capital are better equipped in activating the creative response to increases in green public demand. This relationship holds across the board, i.e., when looking at green patents (Panel A), green process patents (Patent B), and green process patent share (Panel C).

In order to test for differences in the type of public procurement, we complement the analysis by differentiating between public demand for green products and public demand for green services. The results of this investigation are reported in Table 5. Columns I and II refer to public procurement expenditures for products, while columns III and IV consider public procurement expenditures for services. Panel A is for the models that use the natural logarithm of total green patents, augmented by 1, as dependent variable; Panel B is for the models that use the natural logarithm of green process patents, augmented by 1, as dependent variable.

Even though we estimate non-significant coefficients of total procurement expenditures for products (PP in column I, Panel A), we estimate a positive and significant coefficient of product GPP (Panel A, column II), suggesting that increases in the public demand for green products are associated with higher rates of firm green innovation. On the other hand, when service-directed PP is considered, we do not estimate a significant coefficient for the public demand for green services (Panel A, column IV), but rather, we estimate a negative, even if weakly significant, coefficient of total procurement for services (Panel A, column III), which might be mostly ascribed to non-green service expenditures (BPP in Panel A, column IV).

In Panel B we look at green process innovation. Results confirm that public demand for green products favors green process patenting. Indeed, we estimate that a 1% increase in product GPP is associated with a 1.7% increase in the number of green process patents (column II of Panel B). The point estimate of procurement for green services is positive

Table 5: Product and service public procurement

	Procurement type			
	Product		Service	
	(I)	(II)	(III)	(IV)
Panel A – Dep. var.: *ln(1 + GT patents)*				
PP	0.032		-0.016*	
	(0.025)		(0.009)	
BPP		0.026		-0.016*
		(0.026)		(0.009)
GPP		0.022***		0.006
		(0.006)		(0.006)
Panel B – Dep. var.: *ln(1 + GT process patents)*				
PP	0.058*		-0.015**	
	(0.035)		(0.006)	
BPP		0.051		-0.014**
		(0.037)		(0.006)
GPP		0.017***		0.009*
		(0.007)		(0.005)
Control variables:				
Firm-level	✓	✓	✓	✓
Sector-level	✓	✓	✓	✓
MSA-level	✓	✓	✓	✓
Fixed effects:				
Firm FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Observations	14369	14369	14369	14369
Adj. R2 (Panel A)	0.88	0.88	0.88	0.88
Adj. R2 (Panel B)	0.79	0.79	0.79	0.79

Dep var: firm log-transformed number (augmented by 1) of green patents in Panel A and green process patents in Panel B. *PP*, *BPP* and *GPP* are, respectively, the log-transformed amount (in 2017 USD, augmented by 1) of total, non-green, and green public procurement expenditures for products (columns I-II) and services (columns III-IV), measured at the MSA-sector (3-digits NAICS) level. Models include the full set of control variables; the estimated coefficients are not reported. Independent variables are lagged by one year. All models are estimated with fixed effects OLS estimators and weighted by the firm number of filed patents averaged over the sample period. Heteroskedastic-robust standard errors, reported in parentheses, are clustered at the firm level. *p<0.1; **p<0.05; ***p<0.01

and significant too, but lower in magnitude (.009, column IV). At the same time, we find a negative association between green process patenting and total procurement expenditure for services (PP), in particular for non-green services (BPP), as indicated by the negative and significant estimated coefficients reported in Panel B, column IV.

We perform a series of robustness checks to our main results reported in Tables 2 and 3. We report the results of these additional tests in Table 6. In the first set of robustness checks, we re-estimate our main models on different sub-samples. First, to show that results are not driven by very large firms, we exclude firms in the top 5% of the sector-year distribution of net sales per employee (column I). Second, to show that results are not driven by firms located in MSAs that receive the largest amount of federal procurement contracts, we exclude firms headquartered in MSAs thar are in the top 5% of MSA-year PP distribution (column II). Similarly, we exclude firms operating in sectors that are in the top 5% of sector-year PP distribution (column III) to rule out the possibility that the results are driven by firms that operate in the sectors more exposed to public procurement. Lastly, in column IV we impose an even stricter restriction, removing firms in the top 5% of MSA-sector-year PP distribution. The results of these tests fully confirm the main findings. Indeed, we estimate positive coefficients of GPP with respect to both total green patents (Panel A) and green process patents (Panel B) across all samples. Precisely, point estimates of GPP reported in Panel A, columns I to IV (where the dependent variable is the natural logarithm of total green patents, augmented by 1) range between .021 and .03 (.028 in Table 2, column IV); point estimates of GPP reported in Panel B, columns I to IV (where the dependent variable is the natural logarithm of green process patents, augmented by 1) range between .015 and .019 (.017 in Table 3, column IV)

The second set of robustness tests concerns the estimation of more demanding specifications in which we add a series of specific fixed effects to the set of control variables included in the main analysis. Precisely, we alternatively include year-MSA fixed effects (column V),

Table 6: Robustness tests

	Sample exclusion				Additional FEs		
	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)
	Panel A – Dep. var.: *ln(1 + GT patents)*						
BPP	0.017	0.033	0.028	0.027	-0.032	0.050	-0.002
	(0.030)	(0.032)	(0.032)	(0.032)	(0.025)	(0.033)	(0.029)
GPP	0.021***	0.028***	0.030***	0.030***	0.020***	0.032***	0.024***
	(0.007)	(0.008)	(0.008)	(0.008)	(0.007)	(0.007)	(0.005)
	Panel B – Dep. var.: *ln(1 + GT process patents)*						
BPP	0.020	0.030	0.021	0.021	-0.023	0.040	-0.016
	(0.042)	(0.041)	(0.039)	(0.039)	(0.017)	(0.033)	(0.021)
GPP	0.015**	0.017***	0.019***	0.019***	0.013*	0.021***	0.018***
	(0.006)	(0.005)	(0.005)	(0.005)	(0.007)	(0.005)	(0.006)
Control variables:							
Firm-level	✓	✓	✓	✓	✓	✓	✓
Sector-level	✓	✓	✓	✓	✓	✓	✓
MSA-level	✓	✓	✓	✓	✓	✓	✓
Fixed effects:							
Firm FE	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓			
MSA x Year FE					✓		
Sector x Year FE						✓	
Sector (NAICS2) x Year FE							✓
State x Year FE							✓
Observations	13684	14158	14150	13947	13886	14308	14281
Adj. R2 (Panel A)	0.88	0.88	0.88	0.88	0.91	0.89	0.91
Adj. R2 (Panel B)	0.81	0.79	0.78	0.78	0.86	0.82	0.86

Dep var: firm log-transformed number (augmented by 1) of green patents in Panel A, green process patents in Panel B. BPP and GPP are, respectively, the log-transformed amount (in 2017 USD, augmented by 1) of non-green, and green public procurement expenditures, measured at the MSA-sector (3-digits NAICS) level. Columns I-IV estimate the main models by excluding from the sample: top 5% firms by sales over employment (column I), top 5% MSA by total PP (column II), top 5% sectors by total PP (column III), top 5% MSAs-sectors combinations by total PP (column IV). Columns V, VI, and VII include, respectively, year-MSA fixed effects, year-sector fixed effects, and year-sector (at NAICS 2-digits level) year-State fixed effects. Models include the full set of control variables; the estimated coefficients are not reported. Independent variables are lagged by one year. All models are estimated with fixed effects OLS estimators and weighted by the firm number of filed patents averaged over the sample period. Heteroskedastic-robust standard errors, reported in parentheses, are clustered at the firm level. *p<0.1; **p<0.05; ***p<0.01

year-sector fixed effects (column VI), and the combination of year-sector (at NAICS 2-digits level) and year-State fixed effects (column VII). We employ these different levels of fixed effects to further control for, respectively, MSA-year specific shocks, sector-year specific shocks, and State-year combined with industry-year specific shocks that might have influenced simultaneously both firm innovation and MSA-sector GPP. The results of these more demanding specifications fully confirm our main findings. Indeed, point estimates of GPP reported in Panel A, columns V to VII (where the dependent variable is the natural logarithm of total green patents, augmented by 1) range between .02 and .032 (.028 in Table 2, column IV); point estimates of GPP reported in Panel B, columns V to VII (where the dependent variable is the natural logarithm of green process patents, augmented by 1) range between .013 and .021 (.017 in Table 3, column IV).

5 Conclusions

This paper presents novel insights into the nexus between public demand for green products and services and firm-level green innovation. Our analysis focuses on US publicly listed companies spanning the period 2004-2016. We gauge public demand for green products and services at the MSA-sector level to capture demand that firms can readily capitalize on. Firm innovation is measured through patenting activity.

The results of our analysis provide intriguing evidence. Firstly, we find that firms respond to increases in public green demand by innovating in green technologies. Secondly, this innovative endeavor is substantial enough to catalyze a significant shift in the firm innovation trajectory. Specifically, we observe a heightened intensity of innovation in green technologies compared to other forms of innovation in response to increases in public green demand. A third noteworthy finding of our study is that the firm response primarily centers on process-related innovations. We argue that this finding stems from the fact that public green demand predominantly targets conventional products and services, necessitating compliance with more stringent environmental standards. Consequently, firms primarily need to adjust their production to meet these new standards, and this adjustment in production to be efficient requires the introduction of new processes. Lastly, we highlight intriguing heterogeneity observed in our analysis. Notably, we find larger effects of GPP in larger and more established firms, as well as in firms that have accumulated substantial stocks of both knowledge and organizational capital over time. This is particularly pronounced in the context of green process innovation, where relatively large, established firms with high levels of organizational capital are more inclined to introduce new green processes. For these firms, process innovation emerges as a pivotal lever for efficiently capitalizing on the opportunities arising from public spending initiatives.

Our study bears several policy implications. First, we highlight that local public demand has a key role in fostering the profound restructuring of the economy that is required for the transition towards sustainability and a zero-carbon economy. Specifically, local public procurement has the potential to tangibly promote the development and diffusion of environmental innovations and, therefore, to contribute to a shift towards environmentally friendly development trajectories. Policymakers can influence the speed and direction of green innovation by demanding specific green goods or services. While the latter are expected to satisfy specific needs of public administrations, the eco-innovations that are produced will be applicable and relevant for a wider set of economic activities, thus carrying important spillovers for potential adopters (Orsatti et al., 2020). As pointed out by Losacker et al. (2023), policymakers are also confronted with the task of ensuring maximum inclusivity in facilitating the shift towards the green transition. Local resource endowment and allocation may, in fact, result in regional divergence or may worsen existing disparities, with environmental innovations emerging and diffusing only in prosperous regions. With respect to that, it must be noted that, while innovation policy tends to be *localized*, environmental policy is normally decided at the national level, hence leading to the additional challenge of balancing the two. Policymakers should adopt a comprehensive and integrated innovation-oriented environmental policy so as to account for the multi-level governance challenges while ensuring the promotion of inclusive local development and green transition (Crespi et al., 2015).

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