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Does Green Public Procurement Trigger Environmental Innovations?

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Abstract

Green public procurement has gained high political priority and is argued to be an effective demand-side policy to trigger environmental innovations. Its implementation usually takes the form of environmental award selection criteria in public procurement tenders. However, there is no direct or broad empirical evidence on its innovation impact. There are even doubts about its effectiveness as an innovation policy tool, as it does not require innovations as part of its contracts and might only influence the selection of awardees in public procurement tenders. We construct a novel firm-level dataset to investigate the effect of winning green public procurement awards on firms' introduction of environmental innovations. Employing cross-sectional difference-in-differences methods, we find that winning green public procurement awards increases a firm's probability of introducing more environmentally friendly products on average by 20 percentage points. We show that this effect is driven by small and medium-sized firms and is not significant for larger firms. There is no significant effect on the introduction of more environmentally friendly processes.

Keywords Green Public Procurement – Environmental Innovation – Demand Pull

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1. Introduction

Public procurement has a large potential as demand-side innovation policy tool (Edler and Georghiou, 2007; Edquist and Zabala-Iturriagagoitia, 2020) and accounted for around 16 percent of the European Union's gross domestic product in 2017 (Becker et al., 2019). Demand-side innovation policies aim to foster the development and diffusion of innovations by increasing the size of their market and reducing their associated demand uncertainties (Caravella and Crespi, 2020; Schmookler, 1996). Public authorities can reduce information asymmetries considering their innovation demand between them and their potential suppliers by using suitably specified calls for procurement tenders. Furthermore, as a result of the sheer size of public procurement, they can ensure a critical market size, which allows firms to realize early economies of scale and a fast amortization of their investments in innovation (Czarnitzki et al., 2020; Edler and Georghiou, 2007).

Directed public procurement aims to fulfill policy goals such as the development and diffusion of innovation or lowering carbon emissions. Whereas public authorities award their regular procurement contracts solely based on the lowest price, directed procurement takes additional award criteria into account (European Commission, 2017b). These additional criteria favor functional and potentially innovative product and process specifications and can include aspects regarding environmental, social, and economic characteristics (Edquist and Zabala-Iturriagagoitia, 2020). Using directed public procurement, therefore, enables public authorities to deviate from choosing the offers with the lowest price and allows them to put weight on other characteristics in the selection of their awardees. Public procurement awards with additional environmental award criteria are known as green public procurement and cover a wide range of environmental characteristics, such as a product's energy usage, the carbon footprint of a production process, or the use of hazardous substances (Baron, 2016; European Commission, 2016). Firms performing better with respect to the named environmental criteria in their offer receive a higher chance of winning a green contract. Thus, even though they do not require environmental innovations, green public procurement tenders reward firms for committing to the introduction of more environmentally friendly products and processes in their offer by increasing their chance of winning a contract.

Green public procurement has a high political priority, as demonstrated by the European Commission's (2020) strategy for smart, sustainable, and inclusive growth or the current discussion about its mandatory introduction within the public procurement regime of the European Union (Pouikli, 2021). Moreover, it is supposed to be "a powerful instrument for stimulating innovations," according to the Commission of the European Parliament (2008, p. 9). There is a growing literature assessing the design of green public procurement and the barriers to its uptake (e.g., Edquist and Zabala-Iturriagagoitia, 2020; Hall et al., 2015; Rainville, 2017; Rossell, 2021). However, despite its high political priority, empirical studies on its impact are limited, focused on specific classes of environmental criteria, and targeted at the effect on environmental outputs and not innovation (for a review, see Cheng et al. 2018). Simcoe and Toffel (2014) show that mandatory green building standards for public buildings in California stimulate the demand of the private sector for green building. Rietbergen and Blok (2013) find that the uptake of CO_2 certificates as award criteria is related to emissions in the Netherlands. Lindström et al. (2020) examine organic food purchases by the public sector in Sweden and find a positive impact on the share and amount of organic agricultural land. Finally, Cerutti et al. (2016) estimate the carbon footprint reduction resulting from procuring organic school catering in Italy, and Alvarez and Rubio (2015) for procuring more environmentally friendly conservation and maintenance services in Spain based on case studies.

The empirical evidence on the impact of other kinds of public procurement, in particular innovative public procurement, on innovation is more advanced (for reviews, see Appelt and Galindo-Rueda, 2016; Mowery and Rosenberg, 1979; Obwegeser and Müller, 2018). In contrast to green public procurement, which rewards innovation by considering environmental characteristics as award criteria, innovative public procurement explicitly requires innovative solutions and yet to be developed technologies as part of its contracts. Czarnitzki et al. (2020) find that firms winning innovative public procurement awards increase their share of turnover with products newly introduced to their portfolio by about seven percentage points. Ghisetti (2017) shows that winning manufacturing firms are 11 percentage points more likely to adopt a sustainable manufacturing technology within the next 12 months. Caravella and Crespi (2020), Guerzoni and Raiteri (2015), and Stojčić et al. (2020) demonstrate the positive interaction of innovative public procurement with other policy tools such as public innovation subsidies and R&D tax credits. Other kinds of public procurement are investigated, for instance, by Lichtenberg (1988), who observes a positive relationship between competitively awarded public procurement contracts and the winning firms' private R&D expenditures in the US. In a similar vein, Draca (2013) finds that procurement by the US Department of Defense has a positive impact on firms' private R&D expenditures and patenting activities.[1]

We provide the first direct and broad evidence on the effect of green public procurement on environmental innovations. As shown, former empirical research on the effect of green public procurement focused on specific environmental criteria and environmental outputs. By contrast, we investigate the effect of winning green public procurement awards covering a high variety of environmental selection criteria on firms' probability i) to introduce new and more environmentally friendly products, ii) to introduce new and more environmentally friendly processes, and iii) to assess demand as a driver of environmental innovations. Our paper is, therefore, also the first to directly test the hypothesis of public procurement creating a demand pull. Previous studies on the impact of public procurement on innovation exclusively investigate the effect on product innovations (e.g., Aschhoff and Sofka, 2009; Czarnitzki et al., 2020; Stojčić et al., 2020), process innovations (Stojčić et al., 2020), innovation efforts (e.g., Caravella and Crespi, 2020; Guerzoni and Raiteri,

[1] Additional studies that consider other types of public procurement and their relationship with the innovation activities of the private sector are, for example, Aschhoff and Sofka (2009), Crespi and Guarascio (2019), Dai et al. (2020), Edquist and Zabala-Iturriagagoitia (2015), Florio et al. (2018), Saastamoinen et al. (2018) and Slavtchev and Wiederhold (2016). These studies focus on the demand by specific public actors, on specific public procurement awardees or on other award processes, such as pre-commercial procurement, which do not meet the definition of innovative or green public procurement as additional award criteria.

2015), or the development and adoption of technologies (e.g., Draca, 2013; Ghisetti, 2017), and, thus, implicitly assume the creation of a demand pull in their analyses.[2]

Our empirical analysis builds on the German part of the European Community Innovation Survey and the Tenders Electronic Daily database. The German Community Innovation Survey is an annual survey constructed as a representative sample of firms with five or more employees in the German manufacturing and service industries and covers numerous questions on firms' introduction of new and more environmentally friendly products and processes in its waves of 2009 and 2015. The Tenders Electronic Daily database covers information on all public procurement contracts awarded in the European Economic Area whose monetary value exceeds the legal thresholds for securing a transparent and competitive procurement process across borders (European Commission, 2017a). We match both waves of the Community Innovation Survey containing information on environmental innovations with the Tenders Electronic Daily database at the firm-level and manually classify all public procurement awards won by firms between 2006 and 2015 into green and non-green awards. Our empirical analysis utilizes the identified award histories of firms, and we estimate the effect of green public procurement by employing cross-sectional difference-in-differences estimations. To test the validity of our estimations, we further combine them with entropy balancing as an alternative method to account for confounding variables (Hainmueller, 2012).

Our results are heterogeneous. Winning green public procurement awards increases the probability of introducing new and more environmentally friendly products on average by 20 percentage points. However, there is no statistically significant effect of winning green public procurement awards on the probability of introducing new and more environmentally friendly processes. A potential explanation for this phenomenon is a possibly stronger focus on product than on process characteristics within the selection criteria of public procurement tenders. There is no significant effect of winning green awards on demand as a driver of environmental innovations for our entire sample. However, subsample regressions reveal that winning green public procurement awards is exclusively statistically significant for small and medium-sized firms. Winning green awards increases their probability of introducing environmental product innovations by 25 percentage points and the probability of demand being a driver of environmental innovations by 26 percentage points. There are no statistically significant effects for the subsample of larger firms, and environmental process innovations remain unaffected for all samples.

These results verify that green public procurement triggers a demand pull for small and medium-sized firms, which leads to the introduction of environmental product innovations. They further imply that the generated incentive to invest in new and more environmentally friendly products seems to be stronger for firms with higher resource constraints, who depend more on winning individual public procurement awards (Aschhoff

[2] Public procurement has the potential to trigger process innovations directly through the inclusion of process specifications as additional selection criteria, and indirectly by requiring the introduction of new processes as part of adding new products or technologies to a firm's portfolio.

and Sofka, 2009; Cecere et al. 2020). Our main findings, therefore, demonstrate the effectiveness of green public procurement as a demand-side innovation policy tool for small and medium-sized firms.

2. Economic Framework

2.1. Environmental Innovations

We follow the European Community Innovation Survey in defining firm-level environmental innovations as the introduction of new or significantly improved products or processes that create environmental benefits compared to a firm's implemented state of the art. The environmental benefits can be the primary objective of the innovation or a side product of other innovative objectives. Moreover, they can occur in the course of production or during the after-sales use of the product by the end user. This definition only considers implemented innovations and includes the introduction of new products and processes by a firm to the market, as well as a firm's adoption of products and processes already existing on the market (Horbach et al., 2012).

Markets provide insufficient incentives for investments in the R&D and diffusion of environmental innovations (Popp et al., 2019). Environmental innovations face the general uncertainties associated with innovations, such as uncertainty during their R&D stage (e.g., Hottenrott et al., 2017; Pindyck, 1991; Pindyck, 1993) or with regard to their demand (e.g., García-Quevedo et al., 2017; Guiso and Parigi, 1999; Tyagi, 2006). Furthermore, they create double externalities as a result of their environmental focus (Fabrizi et al. 2018; Popp et al., 2019; Rennings, 2000). First, they reduce negative externalities resulting from the environmental burden generated by the use or the production of a product. Environmental burdens generate costs beyond the individual firm. However, they are not priced by the market, and firms, therefore, have no incentive to decrease their pollution to the socially optimal level. Second, environmental innovations cause positive externalities by generating knowledge spillovers. The introduction of environmental innovations adds to markets' public knowledge stock and consequently eases imitation and follow-on inventions. However, firms cannot utilize the additional benefits generated by their environmental innovations and thus, again, create fewer than is socially optimal. Therefore, policy interventions are necessary to provide the socially optimal level of investments in environmental innovations.

2.2. Green Public Procurement as Demand-Side Innovation Policy

Previous literature identifies demand as one of the main drivers of environmental innovations (e.g., Cecere et al., 2020; Costantini et al., 2015/17; Ghisetti, 2017; Horbach et al., 2012; Kesidou et al., 2012; Peters et al., 2012; Veugelers, 2012). However, Cheng et al. (2018) stress in their literature review that there is limited empirical and theoretical research on green public procurement as a demand-side innovation policy for environmental innovations.[3]

Demand-side innovation policies generally aim to promote the development and diffusion of innovations by expanding the size of their market and decreasing their associated demand uncertainties (Caravella and Crespi, 2020; Schmookler, 1996). Public procurement has the potential to foster innovations on both counts. First, public authorities can lower information asymmetries with regard to their innovation demand between them and their potential suppliers by suitably specifying their calls for tenders. Second, they can provide a critical market size, which allows firms to realize early economies of scale and a fast amortization of their investments in innovation (Edler and Georghiou, 2007).[4]

Regular public procurement tenders aim at purchasing existing products for the lowest possible price and are not targeted at fostering the development or diffusion of innovations. They only consider the lowest price criterion in their selection of an awardee, and the firm offering the lowest price for the product sought wins the contract. Directed public procurement considers additional award selection criteria and has the objective of fulfilling various additional policy goals. Green public procurement is a subcategory of directed public procurement focused on environmental objectives. Following the Commission of the European Parliament (2008, p. 4), green public procurement is "a process whereby public authorities seek to procure goods … with reduced environmental impact throughout their life cycle when compared to goods … with the same primary function that would otherwise be procured." It is argued to be "a powerful instrument for stimulating innovations" (p. 9) and usually implemented through the inclusion of additional environmental award criteria. These additional environmental criteria favor functional product and process specifications and include aspects regarding environmental characteristics, such as a product's energy usage, its recyclability, the existence of an environmental management system, or the carbon footprint of a production process (Baron, 2016; European Commission, 2016). Firms performing better regarding the named environmental criteria in their offer have a higher chance of winning the tender.[5] Thus, green tenders do not require environmental innovation, but reward firms for committing to the introduction of more environmentally friendly products and processes by raising their chance of winning the contract.[6] Green public procurement differs in this respect from innovative public procurement. Innovative public procurement corresponds to directed public procurement targeting innovation and explicitly requiring

[3] Rainville (2017) builds the most comprehensive theoretical framework on green public procurement and innovation. It focuses on the relevance of standards in green tenders and the different effects of regular, innovative, and pre-commercial procurement on the creation of incremental innovations, drastic innovations and their diffusion.
[4] Therefore, even though public procurement can decrease average production costs by allowing early economies of scale, it is similar to inducement prizes, which reward innovation, but leave the risk of development to the inventors (Czarnitzki et al., 2020).
[5] An extensive practical guide for the implementation of green public procurement in the European Union is provided by the European Commission (2016).
[6] The made offer is legally binding, and non-compliance can lead to legal consequences, such as a reclamation of funding by the contracting public authorities (European Commission, 2016).

innovative aspects, such as the development of new technologies, as part of its contract criteria (Czarnitzki et al. 2020).

Table 1 provides an example adapted from Baron (2016) on an invitation for tenders to procure a car ferry in three forms: i) regular public procurement with no additional criteria, ii) green public procurement with additional environmental criteria, and iii) a combination of green and innovative public procurement with additional environmental criteria and requiring innovative aspects.[7] The original case corresponds to the example including environmental criteria and innovative aspects. As a result of the procurement contract, the worldwide first completely electric large ferry started its operation and the awarded shipbuilder Fjellstrand AS received 53 additional orders for the same type of electric ferry until 2018 (Energiezukunft, 2018).

Table 1: Examples of public procurement tenders*

In 2010, the Norwegian Ministry of Transport launched a competition for a car ferry. The successful bidder would be awarded a ten-year concession contract.

Tenders of potential contractors are evaluated on the basis of the following criteria and weights:

No additional criteria
- Price (100%)

Environmental criteria
- Price (60%)
- Quality (40%), as the sum of:
    - Energy use per passenger car-km (18%)
    - Total energy usage per year (9%)
    - Tons of CO_2 emitted per year (9%)
    - Kilograms of NOx emitted per year (4%)

Environmental criteria and innovative aspects
The Norwegian Public Roads Administration required a minimum 15–20% improvement in energy efficiency over the existing diesel-powered ferry.
- Price (60%)
- Quality (40%), as the sum of:
    - Energy use per passenger car-km (18%)
    - Total energy usage per year (6%)
    - Tons of CO_2 emitted per year (6%)
    - Kilograms of NOx emitted per year (4%)
    - Innovation (6%)

*The original example is taken from Baron (2016) and corresponds to the case with environmental criteria and innovative aspects.

Previous literature shows the positive impact of winning innovative public procurement awards on firms' innovation activities (Caravella and Crespi, 2020; Czarnitzki et al., 2020; Guerzoni and Raiteri, 2015; Stojčić et al., 2020). Ghisetti (2017) even demonstrates a positive effect on the adoption of sustainable manufacturing technologies. However, innovative public procurement explicitly requires innovation

[7] Innovative public procurement is no subcategory of green public procurement. Innovative aspects can also target non-environmental characteristics, such as product usability and costs-effectiveness.

activities as part of its contracts, and Czarnitzki et al. (2020) and Caravella and Crespi (2020) do not find a relationship between innovation and non-innovative public procurement. The effect of green public procurement, which rewards but does not require environmental innovations, therefore needs further investigation (Cheng et al., 2018). This notion becomes even stronger taking into account that participating in tenders for green public procurement contracts is not mandatory. Firms can freely choose to participate or not. Consequently, green public procurement will only trigger environmental innovation if firms consider participating and adapting to the environmental criteria as profitable and invest in more environmentally friendly products and processes. If green public procurement tenders only attract firms already operating environmentally friendly and without the intention of introducing further innovations, it will only impact the selection of winning firms (Lundberg et al., 2015).[8]

3. Legal Background

The legal grounds for the use of green public procurement within our analysis, which builds on the German Community Innovation Surveys of 2009 and 2015, are the Helsinki Bus Case C-513/99, the Wienstom Case C-448/01 and the new version of §97 para 4 in the German Competition Act. The Helsinki Bus Case in 2002 and the Wienstom Case in 2003 established green public procurement within the entire European Union. At this time, Article 36 92/50/EEC was in force, and European law allowed public authorities to award procurement contracts based on the economically most advantageous tender or the lowest price criterion. The economically most advantageous tender allowed authorities to add various additional economic selection criteria, such as technical merit, functional characteristics, or delivery dates, to the price on the condition that they:

- were directly related to the characteristics of the contractual item,
- did not allow the public authority to freely choose between competing applicants and
- were clearly named in the tender documents.

Environmental criteria were not explicitly listed as potential economic selection criteria, which gave rise to the Helsinki Bus and Wienstrom cases.

The Helsinki Bus case established the legal basis for adding environmental criteria focused on *product* characteristics as selection criteria. The city of Helsinki awarded a contract for operating its urban bus network based on the most economically advantageous tender. It decided to award the public procurement contract to HKL–Bussiliikenne, the final determining criteria being the firm’s offer to use busses with low nitrogen oxide and noise emissions. Concordia Bus Finland, another applicant for the award, contested this decision, inter alia, because the existing public procurement law would support additional economic, but no additional environmental criteria. The Court of Justice of the European Union rejected this contestation,

[8] In this case, green public procurement would not trigger environmental innovations, but it could still counteract a lack of private demand for green products and processes and incentivize firms to stay environmentally friendly.

thereby generating the first legal case in the European Union for the inclusion of environmental product characteristics as award criteria.

The inclusion of environmental criteria focusing on production *processes* was legally established in the Wienstrom case. The Republic of Austria invited tenders for the award of supplying all Federal administrative offices in the State of Carinthia with electricity in 2001. In its invitation for tenders, it gave considerable weight to supplying electricity produced from renewable sources. The firm Wienstrom contested this selection criterion after losing the award competition. However, the Court of Justice of the European Union rejected the contestation challenge in 2003, establishing a case for the use of environmental criteria targeting production processes.[9]

The introduction of the new version of §97 para 4 in the German Competition Act in 2009 further clarified the inclusion of environmental criteria in the award process of German public authorities.[10] The directive states that, for contract execution, additional criteria can be requested from the contractor that concern social, environmental, or innovative aspects. With this, procurers were *explicitly* invited to prepare calls for tenders that contain environmental criteria as part of their contracts. Moreover, the directive introduced the possibility to include innovative solutions and yet to be developed technologies within public procurement contracts.[11]

4. Data Preparation

4.1. Data Bases

The German part of the European Community Innovation Survey forms the core of our sample and is augmented with information from the Tenders Electronic Daily database and the German Patent and Trademark Office. The three datasets are matched at the firm-level, based on a string matching of the firms' names and addresses as provided by the ZEW–Leibniz Centre for European Economic Research.[12] Our final dataset corresponds to an unbalanced panel covering the reference years 2008 and 2014, 6,373 unique firms, and 7,224 firm-year observations.

The German Community Innovation Survey is an annual survey collected by the ZEW on behalf of the German Federal Ministry of Education and Research. It is constructed as a representative sample of firms in the German manufacturing and service industries with five or more employees and focuses on gathering information about a variety of firms' innovation activities (Peters and Rammer, 2013). In addition to detailed

[9] The European Commission (2021) provides a detailed description of the rulings.
[10] The directive was the German enforcement of the directives 2004/18/EC and 2004/17/EC of the European Parliament and the Council.
[11] See Czarnitzki et al. (2020) for a more detailed discussion of innovative public procurement in Germany.
[12] The ZEW matched the German Community Innovation Survey to public procurement awards from the Tenders Electronic Daily database for the years 2006 to 2015 and patent applications to the German patent office between 1896 and 2017.

information about innovations at the firm-level, the dataset also contains information about firm performance, such as revenues, exports, profit-to-sales ratios and employee numbers. Most importantly for our analysis, there are different focus topics each year, which cover additional questions. However, these are not repeated annually but within longer time intervals. In the 2009 and 2015 surveys, environmental innovations were such a focus topic. Our analysis thus covers these surveys' corresponding reference years, 2008 and 2014.

The Tenders Electronic Daily database is provided by the European Commission. It contains information about all public procurement contracts awarded in the European Economic Area, whose monetary value exceeds the Commission's thresholds for securing a transparent and competitive procurement process across borders (European Commission, 2017a).[13] However, publishing information on awards with a monetary value below the defined thresholds is considered good practice (TED, 2020). Thus, a non-negligible number of awards with lower monetary values are presented as well. The data is collected by the European Commission and is taken directly from standard procurement forms completed by the procuring authorities.[14] Along with the date of the procurement award and the name of the winning firm, the database contains information about the selection criteria for awarding the procurement contract. For the analysis in this paper, all published awards won by German firms between 2006 and 2015 are considered.[15]

Patent information stems directly from the German Patent and Trademark Office and covers all applications the office received within the period from 1896 to 2017. Inter alia, the database includes information on names and addresses of patent applicants, application dates, and each application's international patent classification.

4.2. Variable Construction

Environmental Innovations – Environmental product innovations are defined as innovations, which reduce environmental externalities arising from the use of the product, while environmental process innovations are defined as innovations, which reduce environmental externalities during the production process on site. In both waves of the Community Innovation Survey, firms are asked about the introduction of their environmental product and process innovations within the last three years and their contribution to environmental protection. In the wave of 2009, firms could choose between "No," "Yes, low contribution," "Yes, medium contribution," and "Yes, high contribution." In the 2015 wave, firms chose between "No,"

[13] Thresholds differ according to time, contracting item, and type of procurer. The threshold limits during our observation period are based on the Directives 2004/18/EC and 2014/24/EU. The smallest threshold covers most services and supplies awarded by central governments. It evolved from EUR 162,000 under directive 2004/18/EC to EUR 134,000 under directive 2014/24/EU. The highest threshold applies to construction contracts awarded by central governments. It changed from EUR 6,242,000 to EUR 5,186,000 from one directive to the other.

[14] The European Commission (2008) lists all contracting public authorities. German contracting authorities are defined as "Local authorities, public law bodies or associations of public law bodies or State undertakings, supplying energy to other undertakings, operating an energy supply network or having power of disposal to an energy supply network."

[15] The Tenders Electronic Daily database has been widely used for the empirical analysis of green public procurement (Rosell, 2021).

"Yes, insignificant contribution," and "Yes, significant contribution." Moreover, environmental product and process innovations are disaggregated into the following externality classes in both waves:

> *Environmental product innovations* are differentiated by new products or services, which (i) reduce energy usage, (ii) reduce water, air, soil, or noise pollution, or (iii) improve recyclability.
>
> *Environmental process innovations* correspond to innovations, which (i) reduce the material use per unit of output, (ii) reduce the energy use per unit of output, (iii) reduce the CO_2 footprint by an enterprise, (iv) reduce air pollution, (v) reduce water or soil pollution, (vi) reduce noise pollution, (vii) replace materials with less hazardous substitutes, or (viii) recycle waste, water, or materials for the firms' own usage.

We use this information to generate dummy variables for the introduction of environmental product innovations and environmental process innovations. The variable for environmental product innovations is equal to zero if a firm answered "No" to all three product externality classes within a year and one otherwise. The variable for environmental process innovations is similarly defined but considers the eight classes of process externalities.

Green Public Procurement Awards – We differentiate between green and non-green public procurement awards by utilizing information on the awards' selection criteria. The Tenders Electronic Daily database covers around 327,000 public procurement awards to German firms during the period 2006 to 2015. We identify 4,764 awards won by 763 firms in our sample. The selection criteria provided in the database are formulated briefly and typically include a list of keywords such as "quality," "know-how," "service," and "environmental factors." We identify public procurement awards as green, whose criteria are related to the 11 environmental externality classes covered by our innovation variables. For this, we manually check the criteria of each award. Our classification yields 242 green public procurement awards of 94 firms. Table 2 presents a summary of the translated keywords related to environmental criteria and covered by the identified green awards. For clarity, we group them into classes. Most awards are part of the broad criteria classes "environment," "sustainability," and "ecology."

We utilize our public procurement classification to create several dummy variables related to a firm's success in winning green and non-green procurement awards. We define a dummy variable equal to one if a firm won at least one green public procurement award within the last three years and zero otherwise. This definition adapts to the three-year interval covered by the environmental innovation variables and the variable serves as an indicator for a firm's current green public procurement success. Furthermore, we generate a dummy variable equal to one if a firm won a green public procurement award at some point between 2006 and 2015 and zero otherwise. This variable differentiates between firms winning green public procurement awards at some point in our observation period and those firms never winning a green award. The same variables are constructed for non-green public procurement awards.

Table 2: Environmental public procurement criteria and keywords*

Criteria classes	Keywords
Environment	Environment, environmental aspects, environmental criteria, environmental sustainability, environmental protection, environmental advantages, environmental evaluation, environmentally friendly products, environmental properties, environmental issues, environmentally friendly, environmental damage, environmental factors, environmentally friendly concept, environmentally friendly technology
Sustainability	Sustainability, sustainable methods, sustainable construction, sustainability concept, development of sustainable concepts and strategies
Ecology	Ecology, ecology evaluation, ecology aspects, ecological quality, ecological concept, ecological advantage
Emissions	Emissions, exhaust emission, emission reduction, transport emissions, CO_2 reduction, CO_2 emissions, CO_2 neutral shipping, CO_2 compensation, emission of volatile organic compounds, vehicle emissions, hybrid vehicles, environmentally friendly vehicle technic, environmentally friendly vehicles
Energy	Energy efficiency, energy savings, energetic concept, energy audits, renewable energy, energetic utilization, green electricity
Noise	Low-noise, noise insulation, noise evaluation
Recyclability	Recycling concept
Soil	Management of soil pollution, solutions for soil pollution
Materials	Proportion of recyclable materials, environmental quality of colors, organic portion of solvents
Life cycle costs	Life cycle costs, LCC
Standards	Number of eco-labels, environmental hallmarks, emission limits, environmental car badges, emission class, environmental management, green IT requirements

*Criteria classes correspond to a grouping of keywords to facilitate receiving an overview. Keywords are translated into English for presentation. The criteria language was German in 239 cases, French in two cases, and Spanish in one case.

Control variables – Previous research identified various factors explaining the introduction of product and process innovations in general and the introduction of environmental innovations in particular (e.g. Czarnitzki et al., 2020; Cecere et al., 2020; Veugelers, 2012). We, therefore, create firm-level control variables from the Community Innovation Survey and the patent database. We consider the current innovation efforts of individual firms by including innovation intensity measured as innovation expenditures over revenues and by creating dummy variables for the occasional or continuous performance of internal R&D activities. We take into account the previously accumulated green and non-green knowledge stock of firms. Patent applications are classified as green and non-green applications following the IPC-based classification of the OECD by Haščič and Migotto (2015).[16] Two separate patent stocks are calculated using the perpetual inventory method with a depreciation rate of 15 percent. Additional innovation funding by public authorities is captured by a public-innovation-funding dummy variable. The number of employees, firm age in years, and two company-group-membership dummies cover firm size, age, and ownership. The membership dummies differentiate between being part of a German or multinational company group. Export revenues consider further multinational activities, and a dummy variable for being located in East Germany accounts for regional differences. Capital intensity and labor intensity are measured as tangible fixed assets and personnel costs over revenues. Detailed industry-year fixed effects based on the three-digit industry level of the NACE Rev. 1.1 classification cover differences between industries and their development over time.

4.3. Descriptive Statistics

Descriptive statistics for the generated variables are shown at the firm-year level in Table 3. The share of environmental product innovations corresponds to 35.0 percent and the share of environmental process innovations to 53.7 percent. The share of firm-year observations introducing both types of environmental innovations simultaneously is 30.8 percent. Our descriptive statistics are thus in line with previous research using the information on environmental innovations from the German Community Innovation Survey (Rexhäuser and Rammer, 2014). At least one green public procurement award is won by 0.5 percent of all observations within the last three years and by 1.5 percent of all observations within the period 2006 to 2015. Non-green public procurement awards are won more frequently. The share of observations winning at least one non-green award within the last three years equals 6.0 percent and the share of observations winning at least one non-green award within the period 2006 to 2015 is 11.9 percent.[17]

A comparison of means in Table 4 shows that firms winning at least one green public procurement award within the last three years are more likely to introduce environmental product and process innovations than non-winning firms. However, even though the comparison provides a first indication of the effectiveness of green public procurement, it might reflect differences in other firm characteristics than the success in winning green public procurement awards.

[16] A detailed list on the identified green IPC classes is available in the annex of Haščič and Migotto (2015).

[17] 37 observations have an innovation intensity above one, and 68 observations have a labor intensity above one. Following the classification of Eurostat (2020), most of these observations are part of knowledge intensive services industries and medium-high-technology or high-technology manufacturing industries. There are 44 observations with an age above 200 years. Most of them are beer breweries, banks, or firms active in the preparation and spinning of textile fibers. Removing the named observations from our estimations does not significantly change our results.

Table 3: Variable definitions and descriptive statistics

Variable descriptions	Mean	Standard deviation	Minimum	Maximum
Introducing new and more environmentally friendly products within the last three years (0/1)	0.350	0.48	-	-
Introducing new and more environmentally friendly processes within the last three years (0/1)	0.537	0.50	-	-
Winning at least one green public procurement award within the last three years (0/1)	0.005	0.07	-	-
Winning at least one green public procurement award between 2006 and 2015 (0/1)	0.015	0.12	-	-
Winning at least one non-green public procurement award within the last three years (0/1)	0.060	0.24	-	-
Winning at least one non-green public procurement award between 2006 and 2015 (0/1)	0.119	0.32	-	-
Number of employees as full-time equivalents	180.595	983.53	0.50	39,900.00
Personnel costs/revenues	0.350	0.26	0.00	6.28
Tangible fixed assets/revenues	0.537	1.68	0.00	30.00
Firm age in years	33.540	38.73	0.50	525.50
Member in a German company group (0/1)	0.147	0.35	-	-
Member in a multinational company group (0/1)	0.167	0.37	-	-
Located in East Germany (0/1)	0.331	0.47	-	-
Export revenues in million EUR	19.250	201.89	0.00	6,624.58
Innovation expenditures/revenues	0.047	0.15	0.00	2.50
Occasional internal R&D activities within the last three years (0/1)	0.121	0.33	-	-
Continuous internal R&D activities within the last three years (0/1)	0.257	0.44	-	-
Receiving public innovation funding within the last three years (0/1)	0.176	0.38	-	-
Green patent stock	0.033	0.38	0.00	12.93
Non-Green patent stock	1.907	17.14	0.00	602.43

The dataset covers the years 2008 and 2014, 6,373 unique firms, and 7,224 firm-year observations.

Table 4: Comparison of means between firms with and without green public procurement

Environmental innovation output	Not winning green public procurement	Winning green public procurement	Differences	P-values
Environmental product innovations (0/1)	0.35	0.53	0.18	(0.05)
Environmental process innovations (0/1)	0.54	0.71	0.17	(0.05)

We employ t-tests on the equality of means assuming unequal variances of the unpaired data.

5. Estimation Strategy

This paper adapts and extends the estimation strategy of Czarnitzki et al. (2020). First, Czarnitzki et al. (2020) examine an innovation equation, which tries to explain the role of innovative public procurement as a driver of product innovations with different levels of novelty. In contrast, we focus our analysis on the role of green public procurement as a driver of environmental product and process innovations. Second, while the information on innovative public procurement in Czarnitzki et al. (2020) is limited to an individual wave of the German Community Innovation Survey, we can utilize two waves and our information on firms' green public procurement award history to employ cross-sectional difference-in-differences estimates.

We modify the cross-sectional difference-in-differences model of Wooldridge (2010) to our setting and define firms awarded green public procurement contracts between 2006 and 2015 as the treatment group and firms not receiving any such contracts as the control group. Formally, we estimate:

$$EI_{it} = \beta_0 + \beta_1 GPP_{it} + \beta_2 GPPE_i + \boldsymbol{X}_{it}\beta_3 + \tau + \varepsilon_{it}, \quad (1)$$

where EI_{it} is defined as the environmental innovation output of firm *i* in the last three years. GPP_{it} is defined as a dummy variable equal to one if a firm won at least one green public procurement award during the last three years and zero otherwise. It is our variable of interest and β_1 corresponds to the difference-in-differences estimate of winning green public procurement. The coefficient β_1 therefore measures the average effect of the treatment on the treatment group (Athey and Imbens, 2006). $GPPE_i$ indicates whether a firm won a green public procurement contract during our observation period from 2006 to 2015. It controls for unobserved group-specific effects between treatment and control group and exploits a firm's entire green public procurement award history available in the Tenders Electronic Daily database. τ represents year-industry fixed effects and controls for industry-specific aggregate year-effects, which are the same across treatment and control group. $\boldsymbol{X}_{it}$ is a vector of time-varying firm-level controls to avoid omitted variables, ε_{it} is the idiosyncratic error term and β_0 is the constant term.

For the difference-in-differences estimate, β_1, to be unbiased and consistent, our model needs the treatment to be unrelated to other factors affecting the outcome and hidden in ε_{it}. Thus, it requires the outcomes of the treatment and control group to develop the same in the absence of any treatment and conditional on the included control variables (Bertrand et al., 2004). These requirements are known as the unconfoundedness and common trend assumptions. The firms of our treatment group win green public procurement awards at different points in time within our observation period. Our estimation model exploits this variation, and our difference-in-differences estimate, therefore, assumes a time-constant treatment effect, as most difference-in-differences applications (Goodman-Bacon, 2021).

Our main estimations of Equation (1) use a linear probability model. Lechner (2010) shows that nonlinear models, such as probit and logit, using the standard difference-in-differences specification require the absence of group-specific effects for a consistent estimation of the difference-in-differences estimate. Therefore, we use nonlinear techniques only as a robustness check and after establishing the absence of significant group-specific differences. We also combine our difference-in-differences estimations with entropy balancing (Hainmueller, 2012). Entropy balancing stochastically assigns weights to the observations of the control group, such that the moments of the group's control variables are the same as those in the treatment group. Using this weighting as a step prior to our main estimations controls for confounding variables outside of the estimation equation and ensures the comparability of the treatment and control group.[18] Entropy balancing, therefore, constitutes an alternative to a variety of widely used data preprocessing methods, such as Mahalanobis distance or propensity score matching, whereas it outperforms them in finite samples with regard to bias reduction and efficiency (Hainmueller, 2012). Standard errors are heteroscedasticity-robust and clustered at the firm-level to avoid Moulton bias.[19] Using bootstrap standard errors or non-clustered heteroscedasticity-robust standard errors does not affect our results.

6. Empirical Results

6.1. Baseline Difference-in-Differences Estimations

Table 5 reports our baseline results. We examine the effect of winning green public procurement awards on the probability of introducing environmental product innovations in Column 1 and on introducing environmental process innovations in Column 2. The results indicate that winning at least one green public procurement award within the last three years increases the probability of introducing new and more environmentally friendly products within the last three years by 20 percentage points. Relative to the mean sample probability of introducing environmental product innovations of 35 percent, this is a relative increase of around 57 percent. There is no significant effect of winning green public procurement on a firm's probability to introduce new and more environmentally friendly production processes. A potential explanation for the weaker and insignificant effect green public procurement on environmental process innovations is a stronger focus on product than on process characteristics within the selection criteria of

[18] A recent application of difference-in-differences estimations with entropy balancing is Freier et al. (2015).
[19] Moulton bias refers to seriously downward biased standard errors resulting from correlated disturbances within firms. For more information, see Moulton (1990) and Bertrand et al. (2004).

public procurement tenders. Horbach et al. (2012) hypothesize that consumers concentrate more on characteristics of products than on those of production processes. Similarly, public authorities might include environmental product characteristics more often within green tenders, and our measure for green public procurement could be too broad to identify an impact on process innovations.[20]

Time-independent differences between firms winning and not winning green public procurement awards between 2006 and 2015 are insignificant. The time-varying control variables predominantly behave the same for environmental process and product innovations. Firm size is statistically significant and positively correlated with innovation probability, and labor intensity measured as personal costs over revenues is statistically significant, but its coefficient is negative. Company-group dummies, age, and capital intensity are not statistically significant. Firms located in East Germany have a statistically significantly lower probability of introducing environmental innovations. All variables related to innovation inputs and knowledge stocks are positively related to introducing environmental product innovations and are statistically significant. The same holds for environmental process innovations other than the coefficients for the green and non-green patent stock. The coefficients of both patent stocks are around a third of the coefficients for product innovations and are not statistically significant.

6.2. Selection into Treatment

Besides directly controlling for confounders, we further investigate the existence of potential selection biases. We estimate the differences between the output means of our treatment and control group in the absence of treatment as a first check. Significant differences imply structural differences between both groups independent of the actual treatment and suggest a selection of firms. Non-significant differences suggest a similar output performance of both groups during the absence of treatment and no selection. Table 6 shows the results of our comparisons for the years 2008 and 2014 separately and jointly. We cannot find any significant differences related to environmental innovation outputs between firms winning green public procurement awards between 2006 and 2015, but not within the last three years, and firms winning no awards. Thus, we do not detect a selection of firms, and the lack of significant differences in 2008 and 2014 indicates a common trend of environmental innovation outputs in the absence of treatment between both years.[21]

[20] Our results for environmental process innovations contradict the results of Stojčić et al. (2020) for innovative public procurement and process innovations. They find an increase in the probability of introducing new or significantly improved processes by 23 percentage points for a sample of around 40,000 firms from eight Eastern and Central European countries. However, they also find a larger impact of innovative public procurement on the probability of introducing a new or significantly improved products.

[21] We cannot reliably estimate output developments of individual firms as a result of the highly unbalanced panel structure of our dataset.

Table 5: Cross-sectional difference-in-differences

	(1) Environmental product innovations (0/1)	(2) Environmental process innovations (0/1)
GPP (0/1)[a]	0.20**	0.10
	(0.09)	(0.10)
GPPE (0/1)[a]	−0.05	0.01
	(0.06)	(0.05)
Ln(employees FTE)	0.01***	0.04***
	(0.00)	(0.00)
Personnel costs/revenues	−0.08***	−0.12***
	(0.02)	(0.02)
Tangible fixed assets/revenues	0.01	0.00
	(0.00)	(0.00)
Ln(firm age in years)	0.00	0.00
	(0.01)	(0.01)
German company group (0/1)	−0.01	0.01
	(0.02)	(0.02)
Multinational company group (0/1)	−0.01	−0.01
	(0.02)	(0.02)
Ln(export revenues + 1)	−0.00	−0.00
	(0.00)	(0.00)
East Germany (0/1)	−0.03**	−0.04***
	(0.01)	(0.01)
Innovation expenditures/revenues	0.16***	0.09*
	(0.05)	(0.05)
Occasional internal R&D (0/1)	0.17***	0.17***
	(0.02)	(0.02)
Continuous internal R&D (0/1)	0.22***	0.22***
	(0.02)	(0.02)
Public innovation funding (0/1)	0.07***	0.04**
	(0.02)	(0.02)
Ln(green patent stock + 1)	0.11**	0.04
	(0.05)	(0.04)
Ln(non-green patent stock + 1)	0.03***	0.01
	(0.01)	(0.01)
Constant	0.21***	0.35***
	(0.03)	(0.03)
R-Squared	0.17	0.21
Observations	7,224	7,224

[a] GPP is defined as winning at least one green public procurement award within the last three years, and GPPE as winning at least one green public procurement award between 2006 and 2015. Estimates are based on a linear probability model. Industry-year fixed effects included. Clustered firm-level standard errors in parentheses. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 6: Mean differences in the absence of winning green public procurement awards

Calculation of mean differences	Environmental product innovations (0/1)			Environmental process innovations (0/1)		
	2008	2014	2008+ 2014	2008	2014	2008+ 2014
Winning green public procurement awards, but not within the last three years (0/1)	0.44	0.23	0.38	0.60	0.67	0.62
Not winning green public procurement awards (0/1)	0.37	0.31	0.34	0.54	0.53	0.54
Difference	0.07	-0.08	0.03	0.07	0.14	0.08
P-value	0.34	0.41	0.55	0.43	0.21	0.16

We employ t-tests on the equality of means assuming unequal variances of the unpaired data.

As a second check, we estimate the relationship between firms' current environmental innovation outputs and winning green public procurement awards in the future as a placebo test (Lechner, 2010). For this purpose, we restrict our estimation sample to the year 2008 and regress environmental innovations on a dummy variable for winning at least one green public procurement award between 2009 and 2015. A positive and significant relationship between the variables would indicate a selection of more environmentally innovative firms into future treatment and, thus, a violation of the unconfoundedness and common trend assumption. Table 7 shows the outcome of this exercise. There is no significant relationship between winning green public procurement awards in the future and current environmental innovation outputs. Thus, there seems to be no selection of more environmentally innovative firms based on receiving treatment in the future.

Table 7: Selection into winning green public procurement awards in the future

	(1) Environmental product innovations (0/1)	(2) Environmental process innovations (0/1)
Winning at least one green public procurement award after 2008 (0/1)	−0.00 (0.07)	−0.02 (0.07)
R-squared	0.16	0.21
Observations	3,844	3,844

Estimation sample is limited to the year 2008. Estimates are based on a linear probability model. Industry fixed effects and control variables are included. Full table available as Table A1 in the Appendix. Heteroscedasticity-robust standard errors in parentheses. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

6.3. Non-Green Public Procurement Awards

To ensure our results are not driven by a general public procurement effect, but are specific to green public procurement, we adapt our baseline estimations. We add dummy variables for winning non-green public procurement awards within the last three years and winning non-green public procurement awards between 2006 and 2015. Table 8 provides the estimation results for this specification and confirms that our results are distinct to green public procurement. The impact of winning green public procurement awards within the last three years on environmental product innovations remains at 20 percentage points and statistically significant. The impact on environmental process innovation stays the same in magnitude and remains insignificant. The coefficients of non-green public procurement are largely insignificant. There is a weakly significant negative impact of winning non-green awards on environmental product innovations. This result follows the argumentation of Edquist and Zabala-Iturriagagoitia (2020). Public procurement tenders without additional selection criteria can prevent innovation. Tenders focused on the purchase of existing products exclude the procurement of qualitatively superior products and thus make product innovations as part of a public procurement contract more difficult. Similarly, public procurement tenders without environmental criteria can incentivize the supply of none or less environmentally friendly products and hinder environmental innovations.

Table 8: Controlling for non-green public procurement awards

	(1) Environmental product innovations (0/1)	(2) Environmental process innovations (0/1)
GPP (0/1)[a]	0.20**	0.10
	(0.09)	(0.10)
GPPE (0/1)[a]	−0.04	0.03
	(0.06)	(0.05)
PP (0/1)[a]	−0.06*	−0.04
	(0.03)	(0.03)
PPE (0/1)[a]	0.03	−0.01
	(0.02)	(0.02)
R-squared	0.17	0.21
Observations	7,224	7,224

[a] GPP is defined as winning at least one green public procurement award within the last three years, and GPPE as winning at least one green public procurement award between 2006 and 2015. PP and PPE are defined the same, but for non-green public procurement. Estimates are based on a linear probability model. Industry-year fixed effects and control variables are included. Full table available as Table A2 in the Appendix. Clustered firm-level standard errors in parentheses. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

6.4. Entropy Balancing and Probit Estimations

As an alternative to including control variables directly within the estimation equation, entropy balancing can be used as a data preprocessing method (Hainmueller, 2012). It stochastically assigns weights to the observations of the control group, such that its control variables' moments are the same as in the treatment group. We balance our sample on the means of our control variables and re-run our baseline estimations excluding them.

Tables A3 and A4 in the Appendix demonstrate the successful balancing. Table A3 shows mean comparisons between the treatment and control group before and after the weighting. All differences are virtually zero after the weighting. Table A4 shows the results of regressing the treatment group indicator, winning at least one green public procurement contract between 2006 and 2015, on the balancing variables. Before weighting the sample, the balancing variables have a high joint-significance level with an F-statistic of 5.20, whereas after the weighting the variables are jointly insignificant with an F-statistic of zero. Table 9 shows the results of our cross-sectional difference-in-differences estimations using the balanced sample. There are no large changes compared to our baseline estimations.

As our previous estimates indicate no significant time-independent difference between our treatment and control group, non-linear models using the standard difference-in-differences specification yield a consistent difference-in-differences estimate under the unconfoundedness and common trend assumptions. Thus, we also repeat our baseline estimations employing a probit model instead of a linear probability model. Our baseline results stay robust, as presented in Table A5. The estimated average marginal effects are similar to the coefficients of our baseline results, and significance levels remain the same.

Table 9: Using entropy balancing to control for confounding variables

	(1) Environmental product innovations (0/1)	(2) Environmental process innovations (0/1)
GPP (0/1)[a]	0.21**	0.04
	(0.11)	(0.10)
GPPE (0/1)[a]	−0.08	0.05
	(0.06)	(0.06)
R-squared	0.28	0.28
Observations	7,224	7,224

[a] GPP is defined as winning at least one green public procurement award within the last three years, and GPPE as winning at least one green public procurement award between 2006 and 2015. Estimates are based on a linear probability model. Year-industry fixed effects are included. Sample is balanced on the means of our control variables. Clustered firm-level standard errors in parentheses. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

6.5. Changes in Public Procurement Policies

The introduction of the new version of §97 para 4 in the German Competition Act in 2009 clarified the inclusion of environmental criteria and introduced the possibility of innovative public procurement. To ensure that our results are not driven by the simultaneity of innovative and green public procurement after 2009, we estimate the relationship between winning green public procurement awards and environmental innovation outputs for the subsample of 2008.[22] We examine the relationship by estimating Equation (1), but including industry instead of industry-year fixed effects. A significant relationship indicates the existence of a green public procurement effect in the absence of innovative public procurement, whereas no significant relationship suggests that our previous results might be driven by innovative green public procurement. The results in Table 10 show that firms winning at least one green public procurement award

[22] A more straightforward way to test for the simultaneity of innovative and green public procurement would be to identify innovative green public procurement contracts. This is not feasible with the limited amount of information on additional selection criteria in the Tenders Electronic Daily database.

have a higher probability of introducing environmental product innovations. Thus, there is a positive relationship between both variables before the introduction of innovative public procurement, and our results do not seem to be driven by the simultaneity of innovative and green public procurement.

6.6. Demand Pull and Subsample Regressions

Previous studies identify a positive relationship of different kinds of public procurement on the innovation activities of firms (e.g. Aschhoff and Sofka, 2009; Draca, 2013; Ghisetti, 2017; Lichtenberg, 1988). Moreover, they implicitly assume the creation of a demand pull as one of the main drivers of this relation. We aim at testing this assumption by estimating the effect of winning green public procurement awards on the probability of demand being a driver of environmental innovations.

We repeat our main estimations using an alternative outcome variable. Both waves of the Community Innovation Survey ask about potential reasons for introducing environmental innovations, the current and expected demand for environmental innovations being one of them.[23] In the wave of 2009, firms chose between "Yes" or "No" to the question of demand being a reason for innovation. In the 2015 wave, they chose between the degrees of importance: "Not relevant," "Low," "Medium," and "High." We use this information and generate a dummy variable equal to one if a firm answered "Yes" in 2009 or at least "Low" in 2015 and zero otherwise. Given that green public procurement triggers a demand pull, our results should be similar to our main estimations when using this variable as an alternative outcome.

Table 10: Excluding innovative public procurement from the estimations

	(1) Environmental product innovations (0/1)	(2) Environmental process innovations (0/1)
GPP (0/1)[a]	0.39^{***}	0.11
	(0.15)	(0.20)
GPPE (0/1)[a]	−0.02	−0.03
	(0.07)	(0.07)
R-squared	0.16	0.21
Observations	3,844	3,844

[a] GPP is defined as winning at least one green public procurement award within the last three years, and GPPE as winning at least one green public procurement award between 2006 and 2015. Regression sample is limited to the year 2008. Estimates are based on a linear probability model. Industry fixed effects and control variables are included. Full table available as Table A6 in the Appendix. Heteroscedasticity-robust standard errors in parentheses. P-values correspond to * p < 0.1, ** p < 0.05, *** p < 0.01.

Table 11 shows the results of repeating our main analysis with the alternative outcome. Column 1 presents the results for our full sample. We find a 14 percentage point increase in the probability of demand being the reason for environmental innovations with a significance level of 0.15. Thus, the magnitude and

[23] The survey does not differentiate between environmental product and process innovations or private and public demand at this point.

significance decreased compared to our results on environmental product innovations. To further examine the relevance of green public procurement in creating demand for environmental innovations, we split our sample into small and medium-sized firms with fewer than 250 employees and larger firms. The primary reason for small and medium-sized firms to offer green products is demand (European Commission, 2013), and the relevance of a demand pull is stronger for them because of their higher resource constraints (Aschoff and Sofka, 2009; Cecere et al. 2020). A significant impact of green public procurement within this subgroup would therefore strengthen the hypothesis of a demand pull being triggered by green public procurement. Table 11 presents the results for the subsample of small and medium-sized firms in Column 2 and the subsample of larger firms in Column 3. Winning at least one green public procurement award within the last three years increases the probability of demand being a reason for introducing environmental innovations within the last three years by 26 percentage points for small and medium-sized firms. There is no statistically significant effect for larger firms.

Repeating the subsample analysis with our outcome variables for environmental product and process innovations in Tables 12a and 12b shows the same pattern: Winning at least one green public procurement award within the last three years significantly increases the probability of introducing environmental product innovations within the last three years by 25 percentage points for small and medium-sized firms, but not for larger firms. Consequently, our results in Tables 11, 12a, and 12b confirm the existence of a demand pull effect for small and medium-sized firms but negate an impact on larger firms. This suggests that the generated incentives to invest in new and more environmentally friendly products are stronger for smaller firms, who potentially depend more on winning individual public procurement awards.

Table 11: Demand as a driver of environmental innovations and firm size

	(1) Demand as driver of innovations (0/1) *-All firms-*	(2) Demand as driver of innovations (0/1) *-Small & medium-sized firms-*	(3) Demand as driver of innovations (0/1) *-Larger sized firms-*
GPP (0/1)[a]	0.14	0.26**	−0.03
	(0.10)	(0.13)	(0.14)
GPPE (0/1)[a]	0.01	0.04	−0.04
	(0.05)	(0.07)	(0.10)
R-squared	0.17	0.15	0.29
Observations	7,224	6,346	805

[a] GPP is defined as winning at least one green public procurement award within the last three years, and GPPE as winning at least one green public procurement award between 2006 and 2015. Estimates are based on a linear probability model. Industry-year fixed effects and control variables are included. Full table available as Table A7 in the Appendix. Clustered firm-level standard errors in parentheses. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 12a: Environmental product innovations and firm size

	(1) Environmental product innovations (0/1) *-All firms-*	(2) Environmental product innovations (0/1) *-Small & medium-sized firms-*	(3) Environmental product innovations (0/1) *-Larger sized firms-*
GPP (0/1)[a]	0.20**	0.25**	0.11
	(0.09)	(0.12)	(0.17)
GPPE (0/1)[a]	−0.05	−0.05	−0.09
	(0.06)	(0.08)	(0.11)
R-squared	0.17	0.16	0.33
Observations	7,224	6,346	805

[a]GPP is defined as winning at least one green public procurement award within the last three years, and GPPE as winning at least one green public procurement award between 2006 and 2015. Estimates are based on a linear probability model. Industry-year fixed effects and control variables are included. Full table available as Table A8a in the Appendix. Clustered firm-level standard errors in parentheses. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 12b: Environmental process innovations and firm size

	(1) Environmental process innovations (0/1) *-All firms-*	(2) Environmental process innovations (0/1) *-Small & medium-sized firms-*	(3) Environmental process innovations (0/1) *-Larger sized firms-*
GPP (0/1)[a]	0.10	0.16	−0.01
	(0.10)	(0.12)	(0.17)
GPPE (0/1)[a]	0.01	0.03	−0.02
	(0.05)	(0.07)	(0.10)
R-squared	0.21	0.19	0.35
Observations	7,224	6,346	805

[a] GPP is defined as winning at least one green public procurement award within the last three years, and GPPE as winning at least one green public procurement award between 2006 and 2015. Estimates are based on a linear probability model. Industry-year fixed effects and control variables are included. Full table available as Table A8b in the Appendix. Clustered firm-level standard errors in parentheses. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

7. Conclusion

Green public procurement has a high political priority and is argued to be a powerful innovation policy. Previous studies on the impact of green public procurement, however, focus on specific environmental criteria and target environmental outputs and not innovation. We, therefore, provide the first direct and broad empirical evidence on the effect of green public procurement on environmental innovations. Specifically, we investigate the effect of winning public procurement awards covering a high variety of environmental selection criteria on firms' probability i) to introduce new and more environmentally friendly products, ii) to introduce new and more environmentally friendly processes, and iii) to assess demand as a driver of environmental innovations. Our paper is, thus, also the first to directly test the hypothesis of public procurement creating a demand pull.

Our empirical analysis utilizes information from the Tenders Electronic Daily database and the German Community Innovation Survey. Using firms' history of public procurement awards, we employ cross-sectional difference-in-differences estimations that allow us to control for time-independent unobserved differences between firms that have and those that have not won a contract. To rule out a potential selection of firms, we examine if winning green awards in the future is related to current environmental innovations and test for output differences in the absence of green public procurement. Our robustness checks include employing different estimation methods, sample splits, and taking non-green and innovative public procurement into account.

The results are heterogeneous. Winning green public procurement awards increases the probability of introducing new and more environmentally friendly products on average by 20 percentage points. There is no statistically significant effect of winning green public procurement awards on the probability of introducing new and more environmentally friendly processes. A potential explanation for this phenomenon is a stronger focus on product than on process characteristics within additional public procurement selection criteria. Our results are robust to employing entropy balancing as an alternative method to account for confounding variables and using probit and linear probability models for our estimations. We cannot find a selection of more environmentally innovative firms into winning green public procurement awards threatening the unconfoundedness and common trend assumption of our difference-in-differences analysis. Regarding non-green public procurement, we find a weakly significant negative impact on environmental product innovations. The positive effect of green public procurement is therefore not driven by a general procurement effect but is specific to awards with environmental criteria. Winning tenders without additional environmental criteria might even hinder the introduction of new and more environmentally friendly products. Innovative public procurement also does not drive our results, as there is a significant relationship between winning green awards and environmental product innovations before its introduction. Therefore, requiring innovative aspects within public procurement tenders might not be a necessary criterion to foster product innovations, but rewarding innovations could provide sufficient incentives.

Investigating the creation of a demand pull demonstrates the importance of green public procurement for small and medium-sized firms. Winning green awards does not significantly affect the probability of demand being a driver of environmental innovations for our entire sample. We thus follow the notion of the demand pull being stronger for small and medium-sized firms and split our sample. Subsample regressions reveal that winning green public procurement awards is exclusively significant for small and medium-sized firms with fewer than 250 employees. Winning green awards increases their probability to introduce environmental product innovations by 25 percentage points and the probability of demand being a driver of environmental innovations by 26 percentage points. We cannot find a significant effect for larger firms. These results verify that green public procurement triggers a demand pull for small and medium-sized firms, which leads to the introduction of environmental product innovations. They further imply that the generated incentives to invest in new and more environmentally friendly products seem to be stronger for firms with higher resource constraints, who depend more on winning individual public procurement awards (Aschoff and Sofka, 2009; Cecere et al. 2020).

Our main findings support the effectiveness of green public procurement as a demand-side innovation policy for small and medium-sized firms and endorse taking the needs of small and medium-sized firms into account within the award process of public procurement contracts (e.g., Hoeckman and Taş, 2020; OECD, 2018). Our findings on non-green and innovative green public procurement provide further insight on the heterogonous effects of public procurement for policy makers. The weakly significant negative effect of non-green public procurement hints at an unintended lock-in effect of non-green procurement, which reduces firms' probability of introducing more environmentally friendly products. The dispensability of innovative requirements in green public procurement tenders for triggering environmental innovation leads to questions concerning the benefits of strict innovation requirements and calls for a direct comparison of the effects of green tenders with and without innovation requirements.

There are several limitations to our analysis. As a consequence of our measure of environmental innovations, we cannot distinguish between environmental innovations that are new to an individual firm and those that are new to an entire market. We, however, expect our results to be driven by firm novelties, as Czarnitzki et al. (2020) cannot find any impact of innovative public procurement, which is arguably a stronger innovation policy than green public procurement, on the success of market novelties of German firms. Furthermore, as a result of using the Tenders Electronic Daily database, our analysis focuses on winning green public procurement awards with an economically significant size. We cannot make any statements about small awards in particular as these might trigger less investment incentives. It is the same for statements on the intensive-margin effects of green public procurement on environmental innovations, as we only examine dichotomous treatment and outcome variables. This limitation is particularly relevant for our findings on larger firms. We cannot find statistically significant extensive-margin effects for this subsample of firms, but winning green public procurement awards might influence larger firms' intensive-margin of environmental innovations.

Several starting points for future research emerge from our analysis. With regard to green public procurement, it seems promising to focus on firms' environmental performance and the novelty of their introduced environmental innovations as alternative outcomes. The interaction of green public procurement with other policies, for example R&D subsidies, is also not yet investigated. Considering the broader literature on public procurement and innovations, our finding that rewarding innovations seems to generate sufficient incentives for product innovations needs further verification and deeper analysis. The same is the case for our statistically insignificant results on environmental process innovations and for larger firms.

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Appendix: Full Tables

Table A1: Selection into winning green public procurement awards in the future – full table

	(1) Environmental product innovations (0/1)	(2) Environmental process innovations (0/1)
GPP after 2008 (0/1)	-0.00	−0.02
	(0.07)	(0.07)
Ln(employees FTE)	0.02***	0.04***
	(0.01)	(0.01)
Personnel costs/revenues	−0.07*	−0.08**
	(0.04)	(0.04)
Tangible fixed assets/revenues	0.00	−0.00
	(0.01)	(0.01)
Ln(age)	0.00	0.01
	(0.01)	(0.01)
German company group (0/1)	−0.02	0.02
	(0.02)	(0.02)
Multinational company group (0/1)	−0.02	−0.01
	(0.02)	(0.02)
East Germany (0/1)	−0.00	−0.00
	(0.00)	(0.00)
Ln(export revenues + 1)	−0.02	−0.03
	(0.02)	(0.02)
Innovation expenditures/revenues	0.11*	0.13*
	(0.07)	(0.07)
Occasional internal R&D (0/1)	0.19***	0.19***
	(0.02)	(0.02)
Continuous internal R&D (0/1)	0.22***	0.22***
	(0.03)	(0.02)
Public innovation funding (0/1)	0.09***	0.07***
	(0.03)	(0.02)
Ln(green patent stock + 1)	0.14**	0.04
	(0.06)	(0.05)
Ln(non-green patent stock + 1)	0.03**	0.00
	(0.01)	(0.01)
Constant	0.21***	0.31***
	(0.04)	(0.04)
R-squared	0.16	0.21
Observations	3,844	3,844

Regression sample is limited to the year 2008. Estimates are based on a linear probability model. Industry fixed effects are included. Heteroscedasticity-robust standard errors in parentheses. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A2: Controlling for non-green public procurement awards – full table

	(1) Environmental product innovations (0/1)	(2) Environmental process innovations (0/1)
GPP (0/1)[a]	0.20**	0.10
	(0.09)	(0.10)
GPPE (0/1)[a]	−0.04	0.03
	(0.06)	(0.05)
PP (0/1) [a]	−0.06*	−0.04
	(0.03)	(0.03)
PPE (0/1) [a]	0.03	−0.01
	(0.02)	(0.02)
Ln(employees FTE)	0.01**	0.04***
	(0.00)	(0.00)
Personnel costs/revenues	−0.08***	−0.12***
	(0.02)	(0.02)
Tangible fixed assets/revenues	0.01	0.00
	(0.00)	(0.00)
Ln(age)	0.00	0.00
	(0.01)	(0.01)
German company group (0/1)	−0.01	0.01
	(0.02)	(0.02)
Multinational company group (0/1)	−0.01	−0.01
	(0.02)	(0.02)
East Germany (0/1)	−0.02**	−0.04***
	(0.01)	(0.01)
Ln(export revenues + 1)	−0.00	−0.00
	(0.00)	(0.00)
Innovation expenditures/revenues	0.16***	0.09*
	(0.05)	(0.05)
Occasional internal R&D (0/1)	0.17***	0.17***
	(0.02)	(0.02)
Continuous internal R&D (0/1)	0.22***	0.22***
	(0.02)	(0.02)
Public innovation funding (0/1)	0.07***	0.04**
	(0.02)	(0.02)
Ln(green patent stock + 1)	0.11**	0.04
	(0.05)	(0.04)
Ln(non-green patent stock + 1)	0.03***	0.01
	(0.01)	(0.01)
R-squared	0.17	0.21
Observations	7,224	7,224

[a] GPP is defined as winning at least one green public procurement award within the last three years, and GPPE as winning at least one green public procurement award between 2006 and 2015. PP and PPE are defined the equally, but for non-green public procurement. Estimates are based on a linear probability model. Industry-year fixed effects and constant are included. Clustered firm-level standard errors in parentheses. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A3: Mean differences of controls before and after entropy balancing

Control variables	(1) GPPE = 1	(2) GPPE = 0 Unbalanced	(3) GPPE = 0 Balanced	(4) (1)–(2)	(5) (1)–(3)
Ln(employees FTE)	5.28	3.55	5.28	1.73***	0.00
Personnel costs/revenues	0.32	0.35	0.32	−0.03	0.00
Tangible fixed assets/revenues	0.52	0.54	0.52	−0.02	0.00
Ln(age)	3.18	3.06	3.18	0.12	0.00
German company group (0/1)	0.30	0.14	0.30	0.15***	0.00
Multinational company group (0/1)	0.26	0.17	0.26	0.10**	0.00
East Germany (0/1)	0.29	0.33	0.29	−0.04	0.00
Ln(export revenues + 1)	−7.97	−6.87	−7.97	−1.10	0.00
Innovation expenditures/revenues	0.01	0.05	0.01	−0.04***	0.00
Occasional internal R&D (0/1)	0.09	0.12	0.09	−0.03	0.00
Continuous internal R&D (0/1)	0.26	0.26	0.26	0.00	0.00
Public innovation funding (0/1)	0.18	0.18	0.18	0.00	0.00
Ln(green patent stock + 1)	0.03	0.02	0.03	0.01	0.00
Ln(non-green patent stock + 1)	0.40	0.26	0.40	0.14	0.00

The weighting is based on the entropy balancing method proposed by Hainmüller (2012). GPPE is defined as winning at least one green public procurement award between 2006 and 2015 and identifies the treatment group. The sample is balanced with regard to the first moment of the presented control variables. We employ t-tests on the equality of means assuming unequal variances of the unpaired data. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A4: Joint significance before and after entropy balancing

	(1) GPPE (0/1)[a] *-Balanced-*	(2) GPPE (0/1)[a] *-Unbalanced-*
Ln(employees FTE)	−0.00	0.01***
	(0.02)	(0.00)
Personnel costs/revenues	0.00	−0.01
	(0.13)	(0.01)
Tangible fixed assets/revenues	−0.00	−0.00
	(0.02)	(0.00)
Ln(age)	−0.00	−0.00
	(0.03)	(0.00)
German company group (0/1)	−0.00	0.01
	(0.07)	(0.01)
Multinational company group (0/1)	0.00	0.00
	(0.08)	(0.01)
East Germany (0/1)	−0.00	−0.00
	(0.07)	(0.00)
Ln(export revenues + 1)	0.00	−0.00***
	(0.00)	(0.00)
Innovation expenditures/revenues	−0.02	−0.01
	(1.35)	(0.01)
Occasional internal R&D (0/1)	0.00	−0.00
	(0.09)	(0.00)
Continuous internal R&D (0/1)	0.00	−0.00
	(0.08)	(0.00)
Public innovation funding (0/1)	0.00	0.01
	(0.08)	(0.01)
Ln(green patent stock + 1)	−0.00	−0.00
	(0.17)	(0.02)
Ln(non-green patent stock + 1)	0.00	−0.00
	(0.04)	(0.00)
Constant	−0.00	0.01***
	(0.02)	(0.00)
F-statistic	0.00	5.20
R-squared	0.00	0.02
Observations	7,224	7,224

[a] GPPE is defined as winning at least one green public procurement award between 2006 and 2015 and identifies the treatment group. Estimates are based on a linear probability model. Clustered firm-level standard errors in parentheses. P-values correspond to * p < 0.1, ** p < 0.05, *** p < 0.01.

Table A5: Cross-sectional difference-in-differences employing probit estimations

	(1) Environmental product innovations (0/1)	(2) Environmental process innovations (0/1)
GPP (0/1)[a]	0.18**	0.10
	(0.08)	(0.10)
GPPE (0/1)[a]	−0.05	0.01
	(0.05)	(0.05)
Ln(employees FTE)	0.01***	0.04***
	(0.00)	(0.00)
Personnel costs/revenues	−0.09***	−0.13***
	(0.03)	(0.03)
Tangible fixed assets/revenues	0.01	0.00
	(0.00)	(0.00)
Ln(age)	0.00	0.00
	(0.01)	(0.01)
German company group (0/1)	−0.01	0.01
	(0.02)	(0.02)
Multinational company group (0/1)	−0.01	−0.02
	(0.02)	(0.02)
East Germany (0/1)	−0.03**	−0.04***
	(0.01)	(0.01)
Ln(export revenues + 1)	−0.00	−0.00
	(0.00)	(0.00)
Innovation expenditures/revenues	0.16***	0.08*
	(0.05)	(0.05)
Occasional internal R&D (0/1)	0.16***	0.17***
	(0.02)	(0.02)
Continuous internal R&D (0/1)	0.21***	0.23***
	(0.02)	(0.02)
Public innovation funding (0/1)	0.06***	0.04**
	(0.02)	(0.02)
Ln(green patent stock + 1)	0.10*	0.05
	(0.06)	(0.06)
Ln(non-green patent stock + 1)	0.03***	0.01
	(0.01)	(0.01)
Pseudo R-squared	0.13	0.15
Observations	7,088	7,080

[a] GPP is defined as winning at least one green public procurement award within the last three years, and GPPE as winning at least one green public procurement award between 2006 and 2015. Industry-year dummies and constant are included. Estimates are based on a probit model. Coefficients are presented as average marginal effects. The number of observations differs due to perfect predictions of few industries-year dummies. Clustered firm-level standard errors in parentheses. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A6: Green public procurement before innovative public procurement – full table

	(1) Environmental product innovations (0/1)	(2) Environmental process innovations (0/1)
GPP (0/1)[a]	0.39***	0.11
	(0.15)	(0.20)
GPPE (0/1)[a]	−0.02	−0.03
	(0.07)	(0.07)
Ln(employees FTE)	0.02***	0.04***
	(0.01)	(0.01)
Personnel costs/revenues	−0.07*	−0.08**
	(0.04)	(0.04)
Tangible fixed assets/revenues	0.00	−0.00
	(0.01)	(0.01)
Ln(age)	0.00	0.01
	(0.01)	(0.01)
German company group (0/1)	−0.02	0.02
	(0.02)	(0.02)
Multinational company group (0/1)	−0.02	−0.01
	(0.02)	(0.02)
East Germany (0/1)	−0.02	−0.03
	(0.02)	(0.02)
Ln(export revenues + 1)	−0.00	−0.00
	(0.00)	(0.00)
Innovation expenditures/revenues	0.12*	0.13*
	(0.07)	(0.07)
Occasional internal R&D (0/1)	0.19***	0.19***
	(0.02)	(0.02)
Continuous internal R&D (0/1)	0.22***	0.22***
	(0.03)	(0.02)
Public innovation funding (0/1)	0.09***	0.07***
	(0.03)	(0.02)
Ln(green patent stock + 1)	0.14**	0.04
	(0.06)	(0.05)
Ln(non-green patent stock + 1)	0.02*	0.00
	(0.01)	(0.01)
Constant	−0.04	0.18
	(0.04)	(0.22)
R-squared	0.16	0.21
Observations	3,844	3,844

[a] GPP is defined as winning at least one green public procurement award within the last three years, and GPPE as winning at least one green public procurement award between 2006 and 2015. Estimation sample is limited to the year 2008. Estimates are based on a linear probability model. Industry fixed effects are included. Heteroscedasticity-robust standard errors in parentheses. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A7: Demand as driver of environmental innovations and firm size – full table

	(1) Demand as driver of innovations (0/1) *-All firms-*	(2) Demand as driver of innovations (0/1) *-Small & medium-sized firms-*	(3) Demand as driver of innovations (0/1) *-Larger sized firms-*
GPP (0/1)[a]	0.14	0.26**	−0.03
	(0.10)	(0.13)	(0.14)
GPPE (0/1)[a]	0.01	0.04	−0.04
	(0.05)	(0.07)	(0.10)
Ln(employees FTE)	0.02***	0.01***	0.06***
	(0.00)	(0.00)	(0.02)
Personnel costs/revenues	−0.05**	−0.05**	−0.03
	(0.02)	(0.02)	(0.11)
Tangible fixed assets/revenues	−0.00	0.00	−0.00
	(0.00)	(0.00)	(0.02)
Ln(age)	−0.01*	−0.01	−0.02
	(0.01)	(0.01)	(0.02)
German company group (0/1)	−0.02	−0.02	−0.03
	(0.01)	(0.01)	(0.05)
Multinational company group (0/1)	−0.00	0.00	−0.01
	(0.02)	(0.02)	(0.05)
East Germany (0/1)	−0.03**	−0.03***	0.02
	(0.01)	(0.01)	(0.05)
Ln(export revenues + 1)	0.00***	0.00*	0.01**
	(0.00)	(0.00)	(0.00)
Innovation expenditures/revenues	0.13***	0.11**	0.43
	(0.05)	(0.05)	(0.31)
Occasional internal R&D (0/1)	0.09***	0.10***	0.07
	(0.02)	(0.02)	(0.07)
Continuous internal R&D (0/1)	0.13***	0.14***	0.06
	(0.02)	(0.02)	(0.05)
Public innovation funding (0/1)	0.08***	0.07***	0.10*
	(0.02)	(0.02)	(0.05)
Ln(green patent stock + 1)	0.08	0.15**	−0.02
	(0.05)	(0.07)	(0.07)
Ln(non-green patent stock + 1)	0.01	0.01	0.01
	(0.01)	(0.01)	(0.02)
Constant	0.13***	0.13***	−0.02
	(0.02)	(0.03)	(0.16)
R-squared	0.17	0.15	0.29
Observations	7,224	6,346	805

[a] GPP is defined as winning at least one green public procurement award within the last three years, and GPPE as winning at least one green public procurement award between 2006 and 2015. Estimates are based on a linear probability model. Industry-year fixed effects are included. Clustered firm-level standard errors in parentheses. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A8a: Environmental product innovations and firm size – full table

	(1) Environmental product innovations (0/1) *-All firms-*	(2) Environmental product innovations (0/1) *-Small & medium-sized firms-*	(3) Environmental product innovations (0/1) *-Larger sized firms-*
GPP (0/1)[a]	0.20**	0.25**	0.11
	(0.09)	(0.12)	(0.17)
GPPE (0/1)[a]	−0.05	−0.05	−0.09
	(0.06)	(0.08)	(0.11)
Ln(employees FTE)	0.01***	0.00	0.05**
	(0.00)	(0.01)	(0.02)
Personnel costs/revenues	−0.08***	−0.07***	−0.10
	(0.02)	(0.02)	(0.12)
Tangible fixed assets/revenues	0.01	0.01	0.00
	(0.00)	(0.00)	(0.03)
Ln(age)	0.00	0.01	−0.01
	(0.01)	(0.01)	(0.02)
German company group (0/1)	−0.01	−0.02	0.06
	(0.02)	(0.02)	(0.06)
Multinational company group (0/1)	−0.01	−0.02	0.02
	(0.02)	(0.02)	(0.06)
East Germany (0/1)	−0.03**	−0.03**	0.03
	(0.01)	(0.01)	(0.05)
Ln(export revenues + 1)	−0.00	−0.00	0.00
	(0.00)	(0.00)	(0.00)
Innovation expenditures/revenues	0.16***	0.15***	0.60**
	(0.05)	(0.05)	(0.27)
Occasional internal R&D (0/1)	0.17***	0.17***	0.13*
	(0.02)	(0.02)	(0.07)
Continuous internal R&D (0/1)	0.22***	0.23***	0.16***
	(0.02)	(0.02)	(0.06)
Public innovation funding (0/1)	0.07***	0.06***	0.14***
	(0.02)	(0.02)	(0.05)
Ln(green patent stock + 1)	0.11**	0.12	0.10
	(0.05)	(0.08)	(0.08)
Ln(non-green patent stock + 1)	0.03***	0.02	0.02
	(0.01)	(0.02)	(0.02)
Constant	0.21***	0.23***	0.04
	(0.03)	(0.03)	(0.16)
R-squared	0.17	0.15	0.33
Observations	7,224	6,346	805

[a] GPP is defined as winning at least one green public procurement award within the last three years, and GPPE as winning at least one green public procurement award between 2006 and 2015. Estimates are based on a linear probability model. Industry-year fixed effects are included. Clustered firm-level standard errors in parentheses. P-values correspond to * p < 0.1, ** p < 0.05, *** p < 0.01.

Table A8b: Environmental process innovations and firm size – full table

	(1) Environmental process innovations (0/1) *-All firms-*	(2) Environmental process innovations (0/1) *-Small & medium-sized firms-*	(3) Environmental process innovations (0/1) *-Larger sized firms-*
GPP (0/1)[a]	0.10	0.16	−0.01
	(0.10)	(0.12)	(0.17)
GPPE (0/1)[a]	0.01	0.03	−0.02
	(0.05)	(0.07)	(0.10)
Ln(employees FTE)	0.04***	0.03***	0.03**
	(0.00)	(0.01)	(0.02)
Personnel costs/revenues	−0.12***	−0.11***	−0.11
	(0.02)	(0.02)	(0.13)
Tangible fixed assets/revenues	0.00	0.00	0.01
	(0.00)	(0.00)	(0.03)
Ln(age)	0.00	0.00	0.01
	(0.01)	(0.01)	(0.02)
German company group (0/1)	0.01	0.02	0.02
	(0.02)	(0.02)	(0.05)
Multinational company group (0/1)	−0.01	−0.01	−0.00
	(0.02)	(0.02)	(0.05)
East Germany (0/1)	−0.04***	−0.04***	−0.02
	(0.01)	(0.01)	(0.05)
Ln(export revenues + 1)	−0.00	−0.00	0.01*
	(0.00)	(0.00)	(0.00)
Innovation expenditures/revenues	0.09*	0.08	0.14
	(0.05)	(0.05)	(0.26)
Occasional internal R&D (0/1)	0.17***	0.18***	0.18***
	(0.02)	(0.02)	(0.06)
Continuous internal R&D (0/1)	0.22***	0.23***	0.18***
	(0.02)	(0.02)	(0.05)
Public innovation funding (0/1)	0.04**	0.04**	0.01
	(0.02)	(0.02)	(0.04)
Ln(green patent stock + 1)	0.04	0.08	−0.05
	(0.04)	(0.06)	(0.06)
Ln(non-green patent stock + 1)	0.01	0.00	0.01
	(0.01)	(0.01)	(0.01)
Constant	0.35***	0.35***	0.43***
	(0.03)	(0.03)	(0.13)
R-squared	0.21	0.19	0.35
Observations	7,224	6,346	805

[a] GPP is defined as winning at least one green public procurement award within the last three years, and GPPE as winning at least one green public procurement award between 2006 and 2015. Estimates are based on a linear probability model. Industry-year fixed effects are included. Clustered firm-level standard errors in parentheses. P-values correspond to * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

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